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MORPHODYNAMICS OF HIGH ENERGY BEACHES AND SURF ZONES: A BRIEF S--ETC(U)
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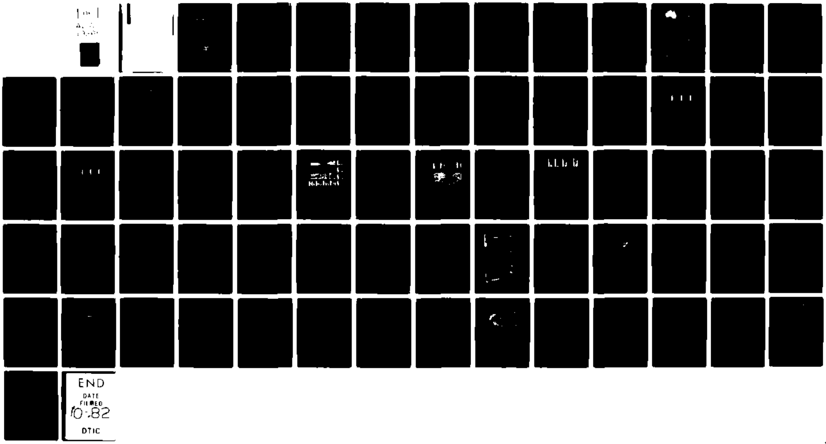

COASTAL STUDIES UNIT TECHNICAL REPORT No. 82/5

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MORPHODYNAMICS OF HIGH ENERGY BEACHES AND SURF ZONES: A BRIEF SYNTHESIS

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CONTENTS

ABSTRACT

A short, simplified synthesis of some results obtained over the period 1979-1982 from a study of beach and surfzone dynamics is presented. The report deals with the different natural beach states, the process signatures associated with these states, state dependent modes of beach erosion, the status of predicting wave- and surf-induced sediment suspension, environmental controls on modal beach state, and the temporal variability of beach state and beach profiles.

Hydrodynamic processes and the relative contributions of different mechanisms to sediment transport and morphologic change differ dramatically as functions of beach state, that is depending on whether the surf zone and beach are reflective, dissipative or in one of the several intermediate states. Depending on beach state, near bottom currents show variations in the relative dominance of motions due to: incident waves, subharmonic oscillations, infragravity oscillations, and mean longshore and rip currents. On reflective beaches, incident waves and subharmonic edge waves are dominant. In highly dissipative surf zones, shoreward decay of incident waves is accompanied by shoreward growth of infragravity energy; in the inner surf zone, currents associated with infragravity standing waves dominate. On intermediate states with pronounced bar-trough (straight or crescentic) topographies, incident wave orbital velocities are generally dominant but significant roles are also played by subharmonic and infragravity standing waves, longshore currents, and rips. The strongest rips and associated

feeder currents occur in association with intermediate transverse bar and rip topographies.

Field observation and modelling of sediment entrainment and suspended load concentrations can be modelled accurately, to bed level, in terms of the skin friction Shield's parameter and a length scale which is also predictable. Important ripple dimensions can also be predicted on the bases of wave height, wave period, depth and grain size. Total or local suspended loads can be predicted as a function of wave characteristics, depth, bed roughness, and sediment fall velocity. In a practical sense, the predicted total quantity of sediment entrained above the bed provides a meaningful index of the potential mobility of the surf zone.

Long-term consecutive surveys of different beaches with contrasting local environmental conditions provide the data sets for empirical-statistical assessment of beach mobility, direction of change and response to environmental conditions. Conditions of persistently high wave energy combined with abundant and/or fine grained sediment results in maintaining highly dissipative states which exhibit very low mobility. Relatively low mobility is also associated with persistently low-steepness waves acting on coarse-grained beach sediments. In such cases the modal beach state is reflective. The greatest degree of mobility is associated with intermediate but highly changeable wave conditions, medium grained sediment and a modest or meagre sediment supply. Under such conditions the beach and surf zone tend to alternate among the intermediate states and to exhibit well developed bar trough and rhythmic topographies. A good association is found between beach state and the environmental parameter $\Omega = H_b/\bar{w}_s T$ where H_b is breaker height, $\bar{w}_s$ is mean sediment fall velocity and T is wave period. Temporal variability of beach state reflects, in part, the temporal variability and rate of change of Ω, which, in turn depends on deepwater wave climate and nearshore wave modifications.

INTRODUCTION

Surf zones and beaches are interesting because they are not all the same. They vary in time with changing wave conditions and both the modal conditions and range of time variations vary spatially with environmental conditions. The temporal and spatial differences can be dramatic; they involve not only differences in depositional morphology but also significant differences in form-coupled hydrodynamic behaviour. The nature and severity of the hazards which are attendant on the rapid advances and retreats of bars and shorelines and on the associated water motions also vary with time and place. In taking a morphodynamic approach to surf zone and beach behaviour, we are concerned with the complete assemblages of depositional forms, hydrodynamic processes, and processes of sediment redistribution; with the patterns, sequences and extents of temporal changes of those assemblages; and with the relationships of the assemblages and their temporal variability to environmental conditions.

The relatively high but temporally and spatially variable energy regimes of Australia have afforded excellent laboratories for studying the full natural range of beach and surf zone morphodynamics. Our field studies of different Australian beaches and surf zones encompass a wide range of temporally and spatially varying environmental conditions, sediment types and morphodynamic states (Wright et al 1979a & b; 1982 a & b; in press; Short, 1979a & b; Wright 1981 and 1982, Short and Wright 1981). These studies point to several important generalizations: (1) Depending on local environmental conditions, sediments, and antecedent wave conditions beach and surf zones may be dissipative, reflective, or in any of at least 4 intermediate states. (2) The relative contributions of incident waves, subharmonic and infragravity standing waves and edge waves, and net surf zone circulations to near bottom currents and resultant sand transport vary with beach state. (3) The actual mechanisms which cause beach cut and the wave energy required to induce beach cut are dependent on beach state. (4) As beach state changes with time, for example in response to changing breaker height, the signature of hydrodynamic processes mutates permitting the evolution of morphodynamic regimes which are free, to varying degrees, from complete forcing by deepwater wave conditons. (5) The modal (or most recurrent) beach state represents a response to the modal breaker characteristics and the prevailing sediment characteristics. (6) The temporal range of beach state and profile changes depend not only on the variability of the deepwater waves but also on the roughness and gradient of the inner continental shelf.

This report is intended to provide a general, and somewhat simplified synthesis of recent results of our study including the most recent developments in predicting modal beach state and beach and surfzone variability in terms of environmental conditions. The more rigorous arguments and mathematical formulations underlying the material in this report may be found in others of our recent publications and reports, particularly Wright et al 1982 a & b; Wright 1982; Wright et al in press; Bradshaw 1982; Nielsen and Green in press; Nielsen in press a & b; Wright 1981 and Short 1981. The aim here is largely to attempt to tie some of the pieces together.

THE STUDY ENVIRONMENTS AND THE DATA SET

This paper synthesizes field results obtained from contrasting environments around the coast of Australia. Although moderate to high wave energy is a general characteristic of most of the study sites, the study includes beaches with varying degrees of topographic sheltering and encompasses prolonged periods over which large temporal variations in energy occurred. Most of the sites are in the microtidal environment of southern and southeastern Australia; however, we include in our discussion some results from a macrotidal beach in Northwestern Australia.

Figure 1 shows the locations of the main study areas. Table 1 lists all of the beaches studied and summarizes the types of data obtained from each. Several beaches on the New South Wales coast provide examples of the full range of dissipative, intermediate, and reflective states owing to varying sediment size and varying degrees of comparmentization and sheltering. These beaches include Seven Mile Beach (dissipative), Moruya (intermediate), Bracken (reflective), Narrabeen-Collaroy (intermediate), Fisherman's (reflective), Palm (intermediate) and Fens (intermediate). The New South Wales coast experiences an east coast swell regime characterized by a highly variable wind-wave climate superimposed on persistent moderate, long-period southeasterly swell (Short and Wright, 1981). Weakly embayed sand beaches alternate with rock headlands. Littoral drift tends to be weak or negligible in comparison to shore normal transport. Semi-diurnal tides have a mean spring range of 1.6 metres (microtidal).

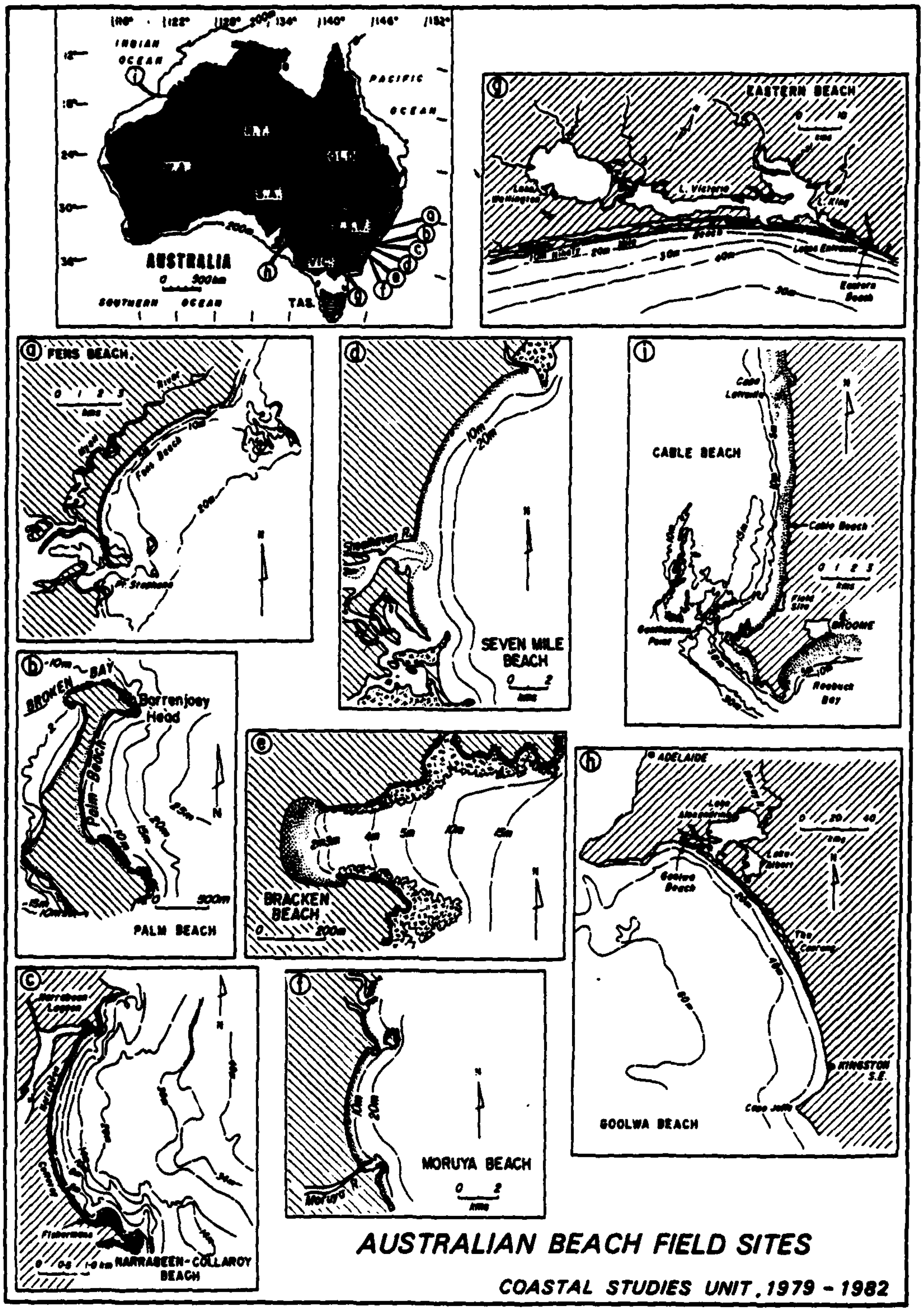

Figure 1: Locations and compartment shapes of major study sites

Table 1: Experiment sites and data collected

TABLE 1: COASTAL STUDIES UNIT - BEACH EXPERIMENTS AND INVESTIGATIONS 1976-1982

No	Location	Date	n	Hb	Beach Type	Spring Tide Range	Experiment	
1	Scotts Head	3.12.78	5	1.5	D	1.6	Surfzone morphodynamics	
2	Grants Beach	5.82	2 20	1	BT	1.6	Beach-offshore survey Box coring	
3	Fens Embayment	1979-81 7.82	18	.5-2	BT RB	1.6 1.6	Beach surveying Suspended sediment	
4	Ocean Beach	8.9.78 2.79	7 6	1 1	D BT	1.6 1.6	Surfzone morphodynamics Surfzone morphodynamics	
5	Pearl Beach	8.77-4.81 11.81	20 15	1 1	R R	1.6 1.6	Surfzone morphodynamics & Box coring and surveying	
6	Palm Beach	1975 1979-80 1980-81 1980	4 10 20 6	1.5 1-2 1-2 1	RB RB - TB	1.6 1.6 1.6 1.6	Beach and offshore survey Surfzone morphodynamics Nearshore dynamics Suspended sediment	
7	N. Avalon Beach	1979	4	1	R	1.6	Surfzone morphodynamics	
8	Narrabeen Beach	1976-82 1981-82 1981-82	95 50 4	.5-3 .5-2 .5-3	R-D RB -	1.6 1.6 1.6	Surfzone morphodynamics Box coring Nearshore dynamics	
9	Collaroy Beach	1976-82	95	.1-.5	R	1.6	Beach surveying	
10	Fishermans Beach	1979-82 1981	24 15	.1-.5 .3	R R	1.6 1.6	Beach surveying Box coring	
11	Dee Why Beach	1977 1977	10 3	.5-2 1.5	RB RB	1.6 1.6	Beach surveying Surfzone morphodynamics	
12	Cronulla Beach	1977 1977	10 5	.5-2 1	R-BT TB	1.6 1.6	Beach surveying Surfzone morphodynamics	
13	Jibbon Beach	1976 1976	10 5	.4 .4	R R	1.6 1.6	Beach surveying Surfzone morphodynamics	
14	Coledale Beach	2.79	3	.5	R	1.6	Surfzone morphodynamics	
15	Werri Beach	2.79 3.82	3 1	.5 .5	LT LT	1.6 1.6	Surfzone morphodynamics Surfzone morphodynamics	
16	N. Seven Mile	1979-82 1980-82	4 12	.5-1.5 .5-2	D D	1.6 1.6	Surfzone morphodynamics Beach surveys	
17	Seven Mile	1982 1980-82 1981-82 3.82	3 12 30 6	1 .5-2 1 1	BT BT BT BT	1.6 1.6 1.6 1.6	Surfzone morphodynamics Beach surveys Box coring (beach and nearshore) Suspended sediment	
18	Moree Beach	1981-82	10 10	1 1	LT LT	1.5 1.5	Surfzone morphodynamics Suspended sediment	
19	Kioloa Beach	1981	12	.5-1.5	TB	1.6	Suspended sediment	
20	Brachen Beach	1976-78	30	.5	R	1.6	Surfzone morphodynamics	
21	Moruya Beach	1976-78	50	.5-1.5	RB	1.6	Surfzone morphodynamics Beach surveys	
22	Eastern Beach	5.81 5.81 5-12.81 5.81 5.81	11 2 10 2 12	.5-2 .5-2 .5-2 1 1	BT BT BT BT BT	1.3 1.2 1.2 1.2 1.2	Surfzone morphodynamics Nearshore dynamics Beach - offshore surveys Box coring Suspended sediment	
23	East Victorian Coast	12.81	35	.5-1.5	R-BT	1.2	Beach surveying and sediment sampling	
24	S.E. of South Aust. Coast	2.79 2.79	45 45	.5-4 .5-4	R-D R-D	.9 .9	Beach surveying Sediment sampling	
25	Goolwa Beach	1-2.80 1-2.80 1-2.80	8 12 -	3-5 3-5 3-5	D D D	.9 .9 .9	Surfzone morphodynamics Beach nearshore surveys Sediment sampling	
26	Cable Beach	11.80 11.80 11.80 11.80	16 2 12 18	.5-2 .5-2 .5-2 .5-2	R & D R & D R & D R & D	9.5 9.5 9.5 9.5	Surfzone morphodynamics Nearshore dynamics Suspended sediment Beach - nearshore surveys	

n — Number of experimental runs; cores or samples collected, surveys conducted etc.
Hb — Modal breaker wave height or range during experiments
Beach Type — See Wright and Short (in press)
Scuba — Indicate SCUBA diving required during experiment

The long, straight relatively uninterrupted beach of East Gippsland (Ninety Mile Beach; Wright et al, 1982 b) provides an example of a storm-wave dominated beach with pronounced intermediate bar-trough topography, strong longshore currents and littoral drift. Highly variable wave conditions result from the frequent passage, particularly in early winter, of southwesterly or southeasterly gales. Spring tide range averages 1.5 metres.

The Goolwa site in the Coorong Region of South Australia is representative of high energy, persistently highly dissipative beach conditions (Wright et al , 1982 a). This beach is 210 km long and faces directly into the perennially high energy west-coast swell of the Southern Ocean. Spring tide range is only 0.8 metres.

A macrotidal environment (spring range 9.5 metres) is the dominant feature of Cable Beach near Broome, Western Australia in the northwest (Wright et al in press). Low to moderate energy wind waves superimposed on low, long period westerly swell characterize the summer wave conditions affecting Cable Beach. During winter, offshore winds prevail maintaining low energy or calm conditions nearshore.

Data on morphologic change are most extensive for the Narrabeen-Collaroy-Fisherman's compartment (Short, 1979 a & b), Moruya Beach (Wright et al, 1979 a; Thom 1981) and Seven Mile Beach. Monthly surveying transects of Narrabeen, Collaroy and Fisherman's beaches have been replicated over a period of 6 years. Daily observations of beach state cover 6 years for Narrabeen Beach and 9 months for Palm Beach. During intensive experiments on all beaches, levelling transects were normally repeated on a daily basis over the experiment period. At less frequent intervals, surveys were extended offshore to depths of 20-30 metres by echo sounding traverses.

Wave and current measurements from within and near the surf zone were made using the field monitoring system described by Bradshaw et al (1978). This system consists of up to 10 strain-gauge type pressure transducers and 12 low inertia bidirectional duct-impellor flow meters. Sensors were connected by cable to chart recording and multiplexing digital tape recording facilities. Response characteristics of the sensors are described by Nielsen and Cowell (1981). In most experiments, data from all sensors in an array were logged simultaneously at intervals of 1 second (greater in some cases) over run lengths of 30 minutes to one hour or more. Raw data were corrected for frequency response characteristics before spectral and statistical analyses were performed.

Suspended sediment concentration profiles under waves were measured using a suction sediment sampler. The device permits simultaneous sampling from 7 levels above the bed by way of thin intake tubes. Concentrations can be measured to within 1 centimetre of the bed. The method is described in more detail by Nielsen and Green (in press) and in Wright et al (1982 b).

MORPHODYNAMIC STATES OF BEACHES AND SURF ZONES

The basic framework for this synthesis is inherited from the earlier morphodynamic beach model discussed by Wright et al (1979 a & b) and Short (1979 a & b). Wright et al (1979 a & b) recognised six commonly observed morphodynamic states, each of which is distinguished by a different association of morphology, circulation, surf behaviour, and resonant frequencies. Short (1979 a & b) showed how different morphological types relate to stages in erosional or accretionary temporal sequences. Both sets of studies were carried out over roughly the same period and in similar environments and the morphologic patterns described by Wright et al (1979 a & b) and Short (1979 a & b) were similar. However, because the earlier studies were carried out independently and with different aims the respective classification schemes exhibited some taxonomic differences which may have been a source of confusion to those wishing to compare results of the two studies. We have attempted to reconcile these discrepancies by means of the modified and updated beach state model shown in Figure 2.

The two extreme states shown in Figure 2 and as previously described by Wright et al (1979 a & b) and Wright (1981) are (1) fully dissipative and (2) highly reflective. Morphologically, these states correspond respectively to flat, shallow beaches with relatively large subaqueous sand storage and steep beaches with small subaqueous sand storage. Morphodynamically the two extremes are distinguished on the basis of the surf-scaling parameter

$$\varepsilon = a_b \omega^2 / g \tan^2\beta \qquad (1)$$

(Guza and Inman, 1975) where a_b is breaker amplitude, ω is incident wave radian frequency ($2\pi/T$; T = period), g is acceleration of gravity and β is beach/surf zone gradient. Complete reflection can be expected when $\varepsilon < 1.0$; however Guza and Inman (1975) and Guza and Bowen (1977) note that so long as $\varepsilon \leq 2.0$-2.5 strong reflection will continue to permit strong standing wave motion,

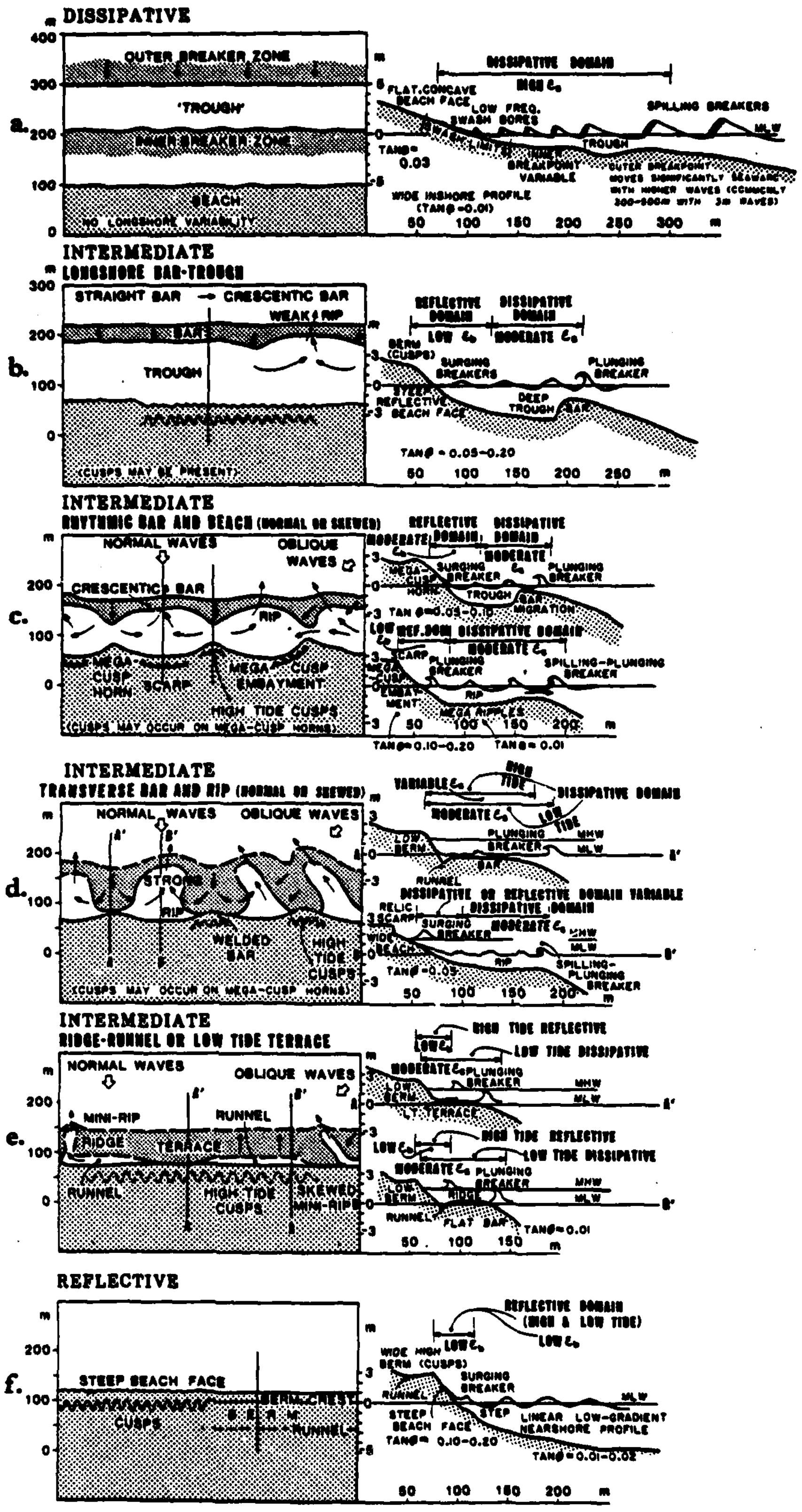

Figure 2: Plan and profile configurations of the six major beach states

surging breakers and resonance, particularly at subharmonic frequencies. Such a situation defines the highly reflective extreme. When $\varepsilon > 2.5$ waves begin to plunge, dissipating energy and when $\varepsilon > 20$ spilling breakers occur (e.g. Galvin, 1972). The surf zone widens and turbulent dissipation of incident wave energy increases with increasing ε.

The dissipative extreme (Fig. 2a) is distinguished by high ε values across the surf zone and on the beach face (ε ranges from 30 to over 100), spilling breakers and approximately saturated surf zones across which bores decay progressively to become very small by the time they reach the subaerial beach (e.g. Wright et al, 1981). Subtle longshore bars are commonly present but longshore rhythms such as "megacusps" are absent. The dissipative extreme is analogous to the "storm" or "winter" profile of seasonally varying beaches; it corresponds to the "Type 1" beach discussed by Wright et al (1979 a) and to Short's (1979 a & b) "Stage 6". To avoid further confusion, we will simply refer to it as "dissipative".

The four intermediate states shown in Figure 2 all possess coexisting dissipative and reflective elements and ε varies significantly across the profile or alongshore. The longshore bar-trough state (Fig. 2b) can develop from an antecedent dissipative profile in an accretionary sequence. It was originally classified by Wright et al (1979 a) as Type 2 and by Short (1979 a & b) as Stage 5. Bar-trough relief is much higher and the beach face much steeper than on the dissipative profile. The bar is the locus of initial wave breaking and is moderately dissipative. In contrast to the dissipative beach, the broken waves cease their depth-dependent decay after passing over the steep inner edge of the bar and reform within the deep (2-3 metres) trough. With respect to the partially dissipated and subsequently reformed waves, the steepened beach face is reflective with local ε commonly around 2. Low-steepness waves surge up the beach face; steeper waves experience a violent collapsing or plunging shore break near the base of the beach face followed by an explosive surge up the subaerial beach. In both cases, runup is relatively high. Cusps are often present in the swash zone.

The "rhythmic bar and beach" state(Fig. 2c; Type 3 of Wright et al, 1979; Stage 4 of Short 1979 a & b) is dynamically similar to the "longshore bar-trough" state inasmuch as a relatively deep trough separates a moderately dissipative and pronounced bar from a generally reflective beach. However, the distinguishing features of the rhythmic bar and beach state are the rhythmic longshore undulations of the crescentic bar and of the subaerial beach. Spacings between crescentic bar horns or shoreline protrusions are typically on the order of 200-300 metres. Weak to moderate rip circulation, similar to that shown in Figure 2c, prevails and the rips are persistent in location. In addition to shore normal variations in reflectivity similar to those which exist on the longshore bar-trough topography, there are also shore parallel variations: embayments are more reflective and shore protrusions more dissipative.

The most pronounced longshore segregation of dissipative and reflective regions occurs in association with the "transverse bar and rip" topography (Fig. 2d; Type 4 of Wright et al, 1979; Stage 3 of Short 1979 a & b). The topography and circulation of this state are generally identical to those of the rhythmic topography discussed by Sonu (1972; 1973). High dissipation and setup over the shallow, flat transverse bars alternate with reflective conditions, low setup and higher runup in embayments which are occupied by relatively strong rips. In an accretional sequence of beach change, the spacings between rips or transverse bars are usually inherited from the antecedent "rhythmic bar and beach state". However the transverse bar and rip state may persist for extended periods during which time it may undergo considerable evolution involving changes in rip frequency and spacing. Most commonly, rip intensity and spacing decrease with decreasing wave energy (e.g. McKenzie, 1958; Short, 1979 a; Wright et al 1979 a & b).

A relatively narrow, moderately dissipative and flat accumulation of sand at or just below low tide level, backed by a steeper beach face which is reflective at high tide characterizes the "ridge and runnel/low tide terrace" state (Fig. 2e; Type 5 of Wright et al, 1979 a; Stage 2 of Short 1979 a & b). Small, weak and irregularly spaced rips related to the atrophying of pre-existing rips may be present. Shore parallel runnels formed by shoreward migration of swash bars over the flat low tide terrace are often present near the break in slope between the beach face and the low tide terrace. Variations in reflectivity versus dissipativeness are largely related to tidal phase: the beach is typically dissipative at low tide and reflective at high tide.

The fully reflective beach state (Fig. 2f) lacks any dissipative elements. Breakers are exclusively surging to collapsing and turbulence related to the "breaking" process is confined to the zone of high runup on the beach face. Immediately beneath the steep, usually linear, beach face is a pronounced step composed of coarser material. The step depth increases with increasing wave height. Seaward of the step the bed slope decreases appreciably. Pronounced and highly rhythmic beach cusps are often present in the swash zone; however, under low energy conditions the beach is often capped by a high straight-crested berm.

SURF-ZONE PROCESS SIGNATURES AND BEACH STATE

Wind-generated waves are the main source of the energy which drives beach changes. However, the complex processes, which operate in natural surf zones and involve various combinations of dissipation and reflection, can lead to the transfer of incident wave energy to other modes of fluid motion, some of which may become dominant over the waves themselves. Since it is primarily the flows near the sediment-water interface which determine the entrainment and ultimate fate of beach and nearshore sediments, it is important to have some appreciation of the relative roles played by these different modes of fluid motion in contributing to the near-bottom flow field and bed shear stresses. For discussion purposes, we may group the important modes of motion into 4 broad categories: (1) oscillatory flows corresponding directly to the incident waves; (2) oscillatory or quasi-oscillatory flows corresponding to standing waves and edge waves at frequencies lower than incident wave frequency; (3) net circulations generated by wave energy dissipation; and (4) non-wave generated currents. (Storm surge is not included in the above list because it is not normally very consequential on the beaches of South-eastern Australia; however in many other environments it is important).

The first category includes the sediment-agitating oscillations, in the frequency band of the deepwater incident waves, due to both broken and unbroken waves. Oscillations in the second category are standing in the shore-normal dimension over a wide range of frequencies; they may be either "leaky" mode standing waves or trapped edge waves. Included are the subharmonic edge waves (at twice the incident wave period) which are readily excited on reflective beaches (Guza and Davis, 1974), long-period infragravity "surf beat" at periods on the order of 1 to 3 minutes (e.g. Huntley et al 1981; Wright et al 1982) and higher frequency infragravity motions at periods of 30-50 seconds (Wright, 1982). The important wave generated currents are longshore currents, rip currents and rip "feeder" currents. The fourth category includes tidal currents and currents generated by local wind shear. Our experiments on the different beach states show that the relative velocities of these different modes of fluid motion are strongly dependent on the state that the beach is in at the time and on local environmental conditions.

The dissipative extreme

Two beaches - Seven Mile Beach on the Australian east coast south of Sydney and Goolwa Beach in South Australia (Fig. 1) provide examples of long, fully dissipative beaches. Both beaches are sinks for fine sands and exhibit very low gradients (tan β = 0.01 - 0.02) and wide, multibarred surf zones (Fig. 2a). Longshore rhythms or significant irregularities are rarely present. During the experiments, significant breaker heights were about 2 metres and 3 metres on Seven Mile Beach and Goolwa Beach respectively;

the respective wave periods were 10 seconds and 12 to 15 seconds. The surf scaling parameter, ε (Eq 1) was on the order of 30 on Seven Mile Beach and 250-400 on Goolwa Beach. On both beaches, waves broke by spilling and dissipated progressively as they crossed the wide surf zone to become very small at the beach face. The more comprehensive data and analyses were from Goolwa Beach; these results indicated a constant ratio between bore heights H and local depth, h, across the surf zone. The ratio $\gamma = H_b/h$ had an average value of 0.42 which is significantly less than is normally assumed (Wright et al, 1982).

Power spectra of surface elevation η, and horizontal near-bottom currents, u and v from Seven Mile Beach and Goolwa Beach have been described in detail by Wright (1982) and Wright et al (1982) respectively. Figure 3 shows typical u spectra from Goolwa. The important feature of these spectra and of all η, u and v spectra from high energy, fully dissipative surf zones is the dominance of wide-banded infragravity energy in the region of 100-200 seconds period. Phase angles of $\pi/2$ between η and u for the infragravity frequencies on Seven Mile Beach and Goolwa Beach indicate that oscillations at those frequencies are consistently standing (Wright, 1982; Wright et al 1982). At Goolwa, the velocity amplitudes of u corresponding to the infragravity "surf beat" were on the order of 1.2 to 1.5 m sec^{-1} accompanying surf beat heights of roughly 1 metre on the beach (Wright et al, 1982). Standing oscillations at subharmonic frequencies are consistently absent from dissipative surf zones. The likelihood that infragravity oscillations are edge waves has been discussed by Holman (1981) and Huntley et al (1981) and for the specific case of Goolwa by Wright et al (1982).

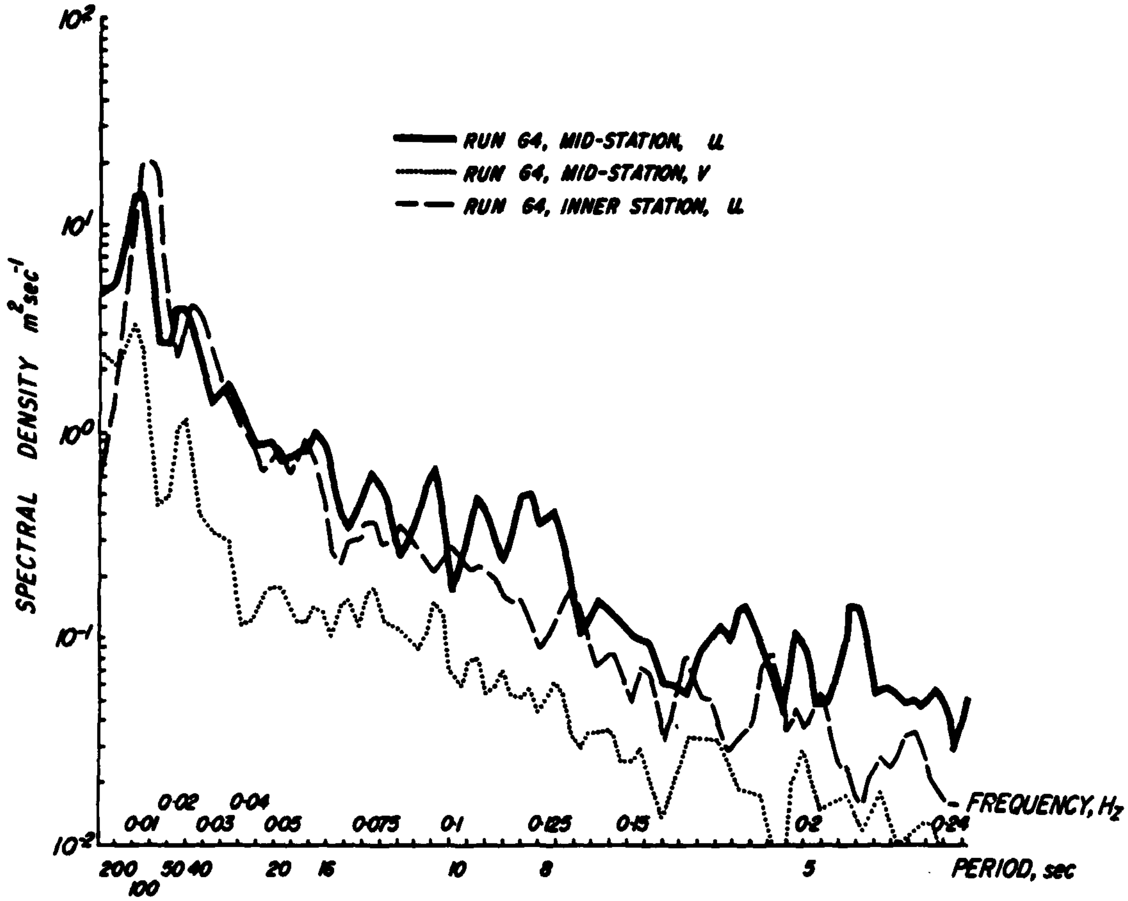

Figure 3: Power spectra of shore normal currents, u, and shore parallel currents, v, from mid and inner surf zone regions of a high energy dissipative surf zone, Goolwa, S.A. (after Wright et al 1982) showing dominance of low frequency infragravity energy.

The net time averaged flows at Goolwa were weak relative to the surf-beat motions. There were no spatially-persistent rips; vertical segregation of shoreward (upper layer) versus seaward (bottom layer) transports generally characterized the shore-normal components of circulation (Wright et al, 1982). It should be pointed out, however, that on strongly embayed and headland bounded beaches such as those near Sydney, very strong, large scale rips frequently accompany the dissipative conditions which occur during storms (Wright et al, 1979 b; Short, 1979 a).

Figure 4 describes the "process signature" observed in the Goolwa surf zone. The bar graphs indicate the relative amplitudes of near-bottom flows associated with the incident waves, the surf beat, and the net transports. The bars are expressed in dimensionless form relative to the observed incident wave related velocities, which are assigned a value of 1. The pronounced shoreward growth of flows due to infragravity oscillations and the strong dominance of those flows in the inner surf zone are the most important features of the graph. This is typical of dissipative beaches in general (e.g. Seven Mile Beach). Recent studies on Torrey Pines Beach (California) by Guza and Thornton (1982) also show that surf-beat dominates runup and that it increases in amplitude linearly with increasing breaker amplitude.

The reflective extreme

Most of our experiments on reflective beach processes were carried out on Bracken Beach south of Sydney (Fig. 1). This beach is similar in morphology and behaviour to other reflective beaches in the region. The persistently low ε values (ε = 1-3) which

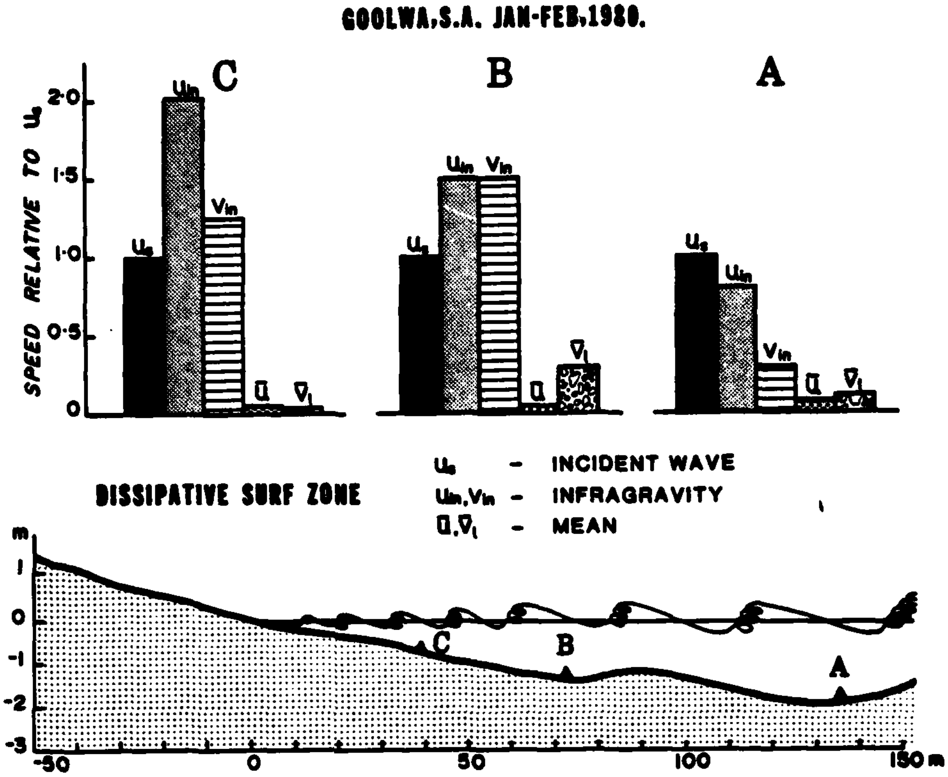

Figure 4: Process signature across a high energy dissipative surf zone, Goolwa, S.A. The bar graphs indicate the <u>relative</u> magnitudes (scaled relative to the significant velocity amplitude u_s of the incident waves) u_s, velocity amplitudes of shore normal and shore parallel flows at infragravity frequencies U_{in}, V_{in}; and $\bar{u}$, $\bar{v}$ net time averaged shore normal and alongshore currents.

characterize these beaches and define their reflective state are consequences of a combination of low refraction coefficients related to the embayed nature of the compartments and steep beach faces ($\tan\beta = 0.1 - 0.15$), commonly but not consistently associated with coarse material. Waves reach the beach face without breaking and surge strongly up the beach or collapse over the step.

Figure 5 shows typical spectra of η and u from Bracken Beach under moderate swell conditions. In sharp contrast to the spectra from the dissipative extreme, most of the energy near the reflective beach is at incident wave frequency and at the first subharmonic of the incident waves (twice the incident wave period). Infra-gravity oscillations are very weak or negligible in most of our data from reflective beaches and are always subordinate to incident waves. The subharmonic oscillations are invariably standing as indicated by the 90° ($\pi/2$) phase angle between η and u. An interpretation of the subharmonic oscillations as edge waves standing alongshore is consistent with the conclusions of Guza and Davis (1974) that subharmonic edge waves of mode zero are the most easily excited and can exist under highly reflective conditions. More detailed descriptions of the reflective beach spectra are given by Wright (1982). Our data indicate that the well developed beach cusps which are normally present on reflective beaches are spaced at one half the predicted length of the zero-mode subharmonic edge waves. Under low energy conditions subharmonic oscillations tend to be of low amplitude relative to incident wave amplitude. However, under conditions of moderate energy long-period swell, the subharmonic oscillations attain amplitudes greater than those of the incident waves at the beach producing accentuated runup

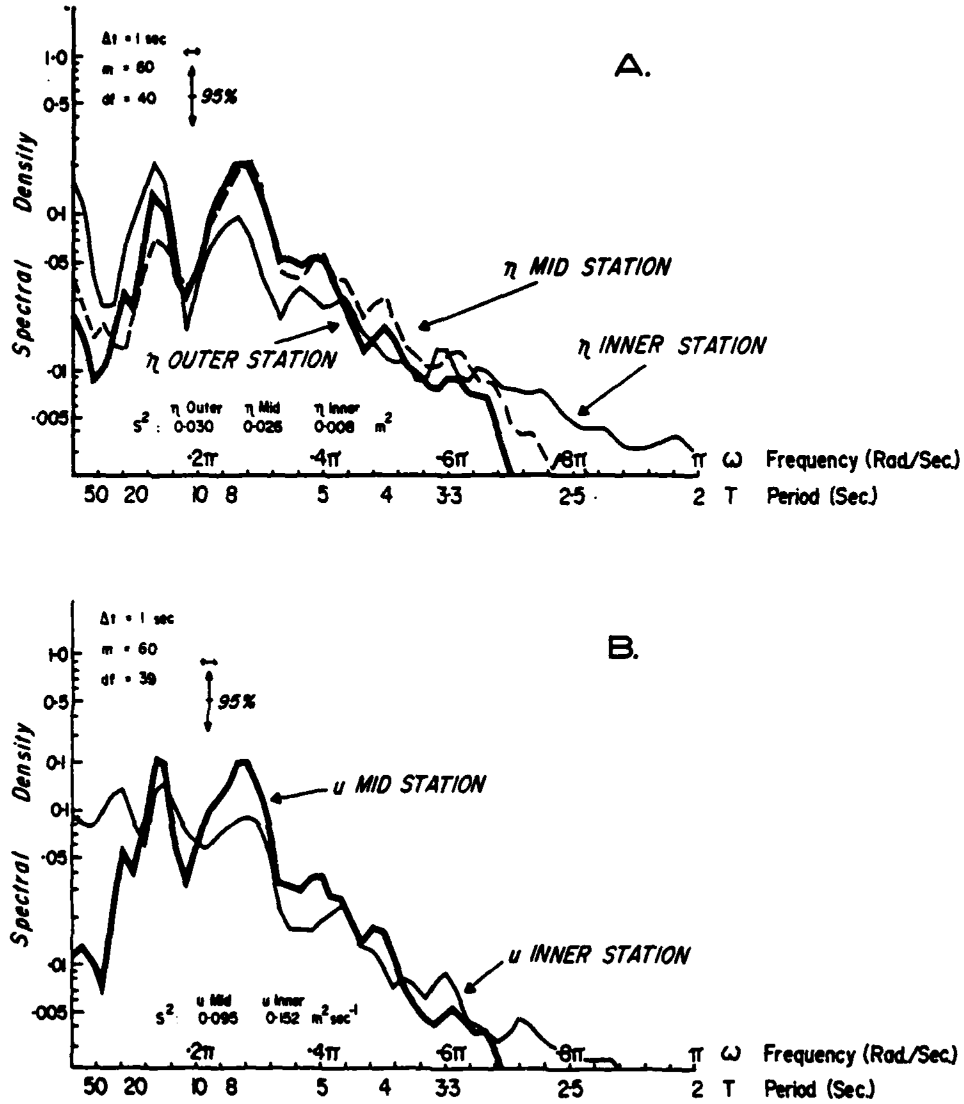

Figure 5: Spectra of water surface elevation, η and shore normal currents, u from a highly reflective beach (Bracken Beach, 10 December 1977) (a) power spectra of η; (b) power spectra of u.

which may overtop the berm crest and initiate subaerial beach cut. Figure 6 shows the typical process signature of reflective beaches (based on data from Bracken Beach) under moderate swell conditions.

Intermediate States

The most complex process signatures are associated with the intermediate beach states *owing to the fact* that those states possess both dissipative and reflective elements. Processes associated with the longshore bar-trough and rhythmic bar and beach states are illustrated by results from Moruya Beach, some of which have been discussed by Wright et al (1979) and Wright (1982) and by more recent and more conclusive results from Eastern Beach in eastern Bass Strait (Fig. 1; Wright et al 1982 b). Figure 7 shows spectra of η and u from the trough and bar regions of pronounced rhythmic bar and beach topography on Eastern Beach, Gippsland, Victoria. The spectra shown in Figure 7, like all spectra from bar-trough and crescentic bar and beach topography on Eastern Beach and on Moruya Beach show dominance of energy at swell frequency but with appreciable standing wave energy over a band which includes both subharmonic and infragravity frequencies. The infragravity standing waves occur at much higher frequencies than in fully dissipative surf zones: typical periods of the dominant infragravity oscillations are on the order of 35 to 50 seconds. Chappell and Wright (1979) and Wright (1982) have discussed these intermediate frequency standing waves and believe that they may be edge waves which initiate the crescentic bar and beach rhythms and that their frequencies may be constrained or selected by the dimensions of the pronounced trough.

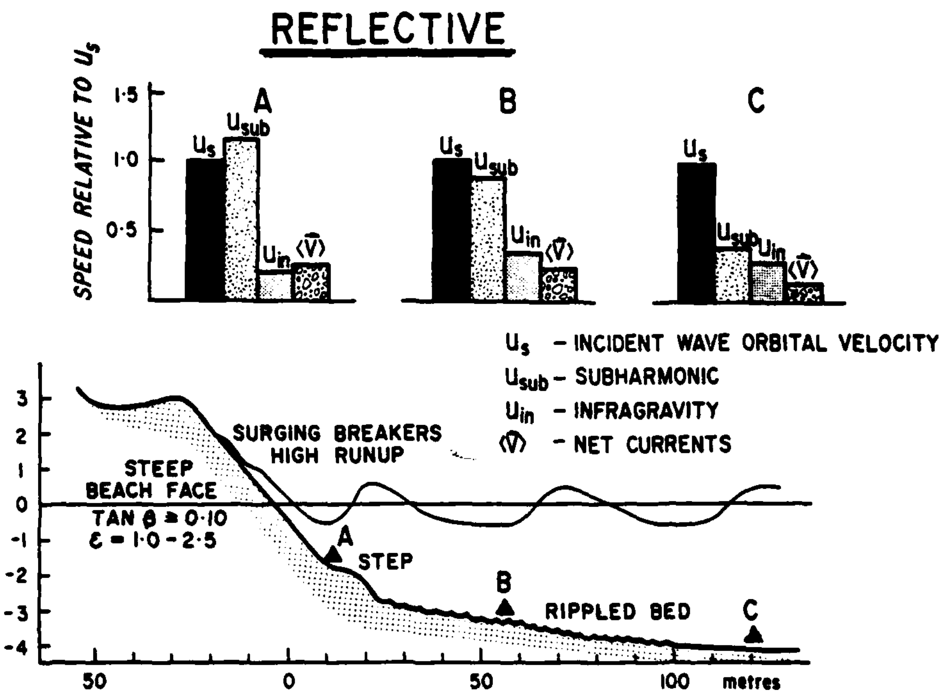

Figure 6: Typical process signature of reflective beaches (based on data from Bracken Beach)

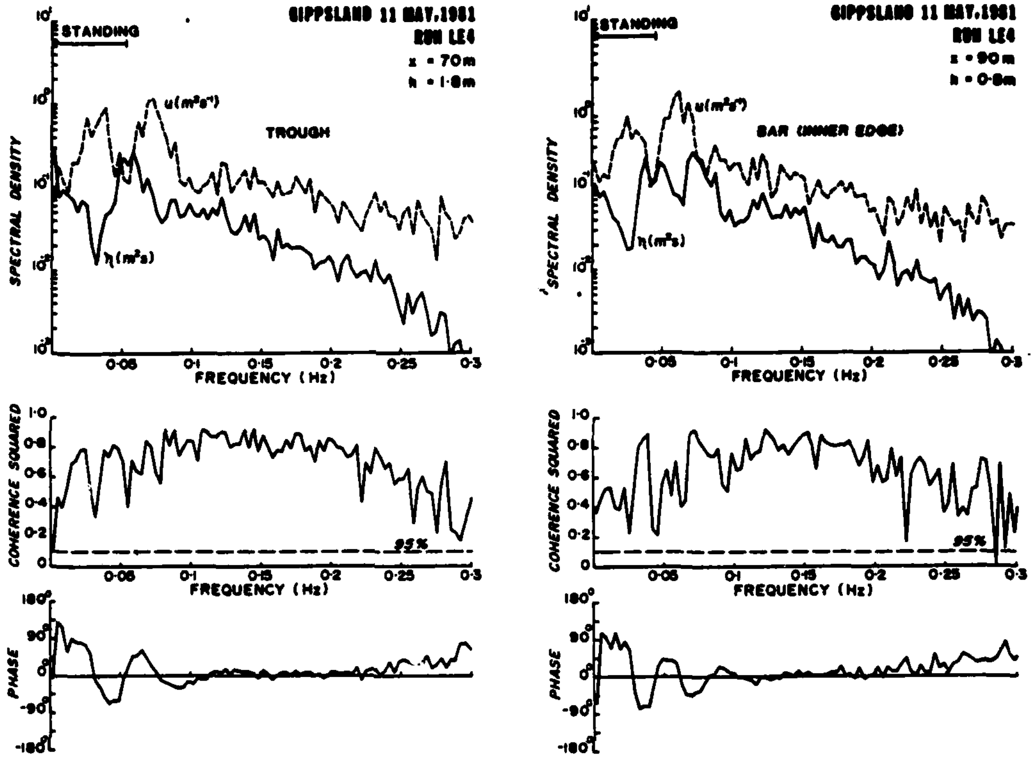

Figure 7: Spectra and cross spectra of η and u from the bar and trough regions associated with a beach state transitional between the longshore bar-trough and rhythmic bar and beach states (Eastern Beach, Gippsland, 11 May 1981). The broad peak at incident wave frequency is dominant; however there is also considerable standing wave energy at relatively short infragravity periods (e.g. around 0.025hz or 40 seconds).

The net mean currents in the presence of bar-trough and crescentic bar and beach topographies are characterized by moderate strength, widely spaced rips and longshore currents within the troughs. On straight bar-trough topographies the rips are relatively weak and usually do not remain fixed in position but migrate alongshore. Their positions become topographically arrested by the crescentic bar and beach topography, however, resulting in intensification of rip currents. When waves break oblique to the shore it is the longshore bar trough and to a lesser degree the crescentic bar and beach topographies which exhibit the strongest longshore currents, with longshore velocity maxima concentrated in the trough. A typical vertical profile of a longshore current, measured in the deep trough of Eastern Beach, Gippsland, Victoria is shown in Figure 8. Prominent features of the Profile (Fig. 8) include the fact that the profile is not all exponential and the relatively high velocities immediately above the bed. In a more detailed discussion of Eastern Beach (Wright et al 1982 b) we attribute these features to the high near-bottom eddy viscosity provided by wave oscillations.

Figure 9 illustrates the net circulation and the process signature associated with crescentic bar and beach topography with a pronounced trough based on our experimental results from Eastern Beach. The histograms indicate the magnitude, relative to the velocity amplitude, u_s, associated with the local incident waves, of near-bed velocities related subharmonic oscillations (u_{sub}) infragravity oscillations (u_{in}, v_{in}), and net time averaged longshore and rip currents ($\bar{V}$) in different regions of the surf zone. Incident waves tend to dominate everywhere but are overwhelmingly dominant over the bar where they initially break. Subharmonic

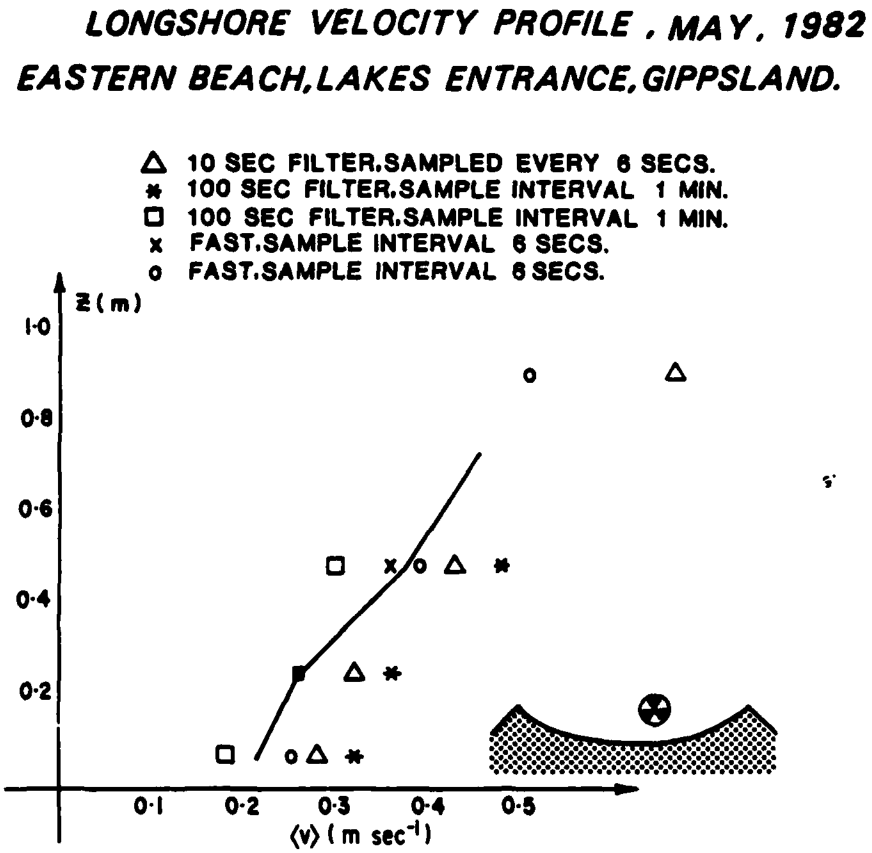

Figure 8: Vertical velocity profile of the longshore current as measured within the trough of Eastern Beach, Gippsland, 13 May 1981. Note the high current speeds on the order of 25 cm sec^{-1} which are present at an elevation of less than 10 cm above the bed.

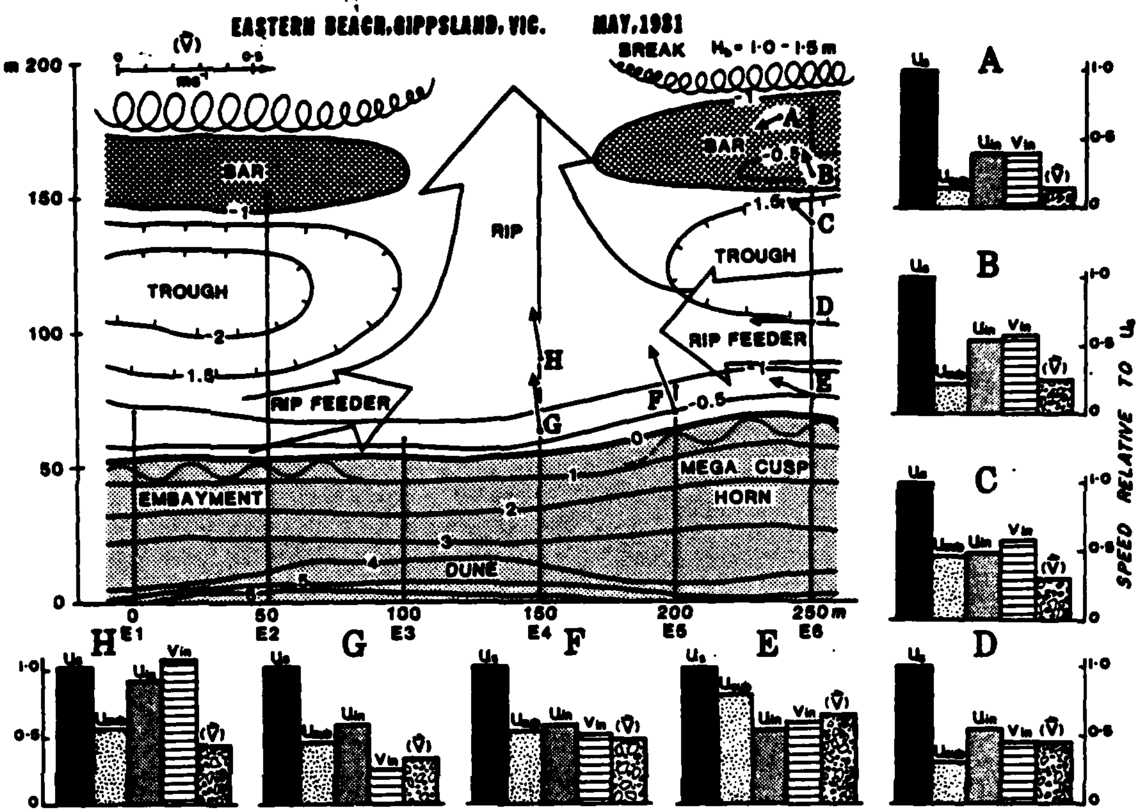

Figure 9: Net circulation pattern and process signature observed in the presence of rhythmic bar and beach topography, Eastern Beach, Gippsland. The broad arrows indicate general circulation based on dye releases. Fine arrows indicate current speeds and directions measured at specific points. As in Figures 4 and 6, the bar graphs indicate the magnitudes relative to incident wave orbital velocities of different modes of horizontal current motion: U_{sub} shore normal currents at subharmonic frequency; U_{in}, V_{in} shore normal and shore parallel currents at infragravity frequencies, $\bar{V}$ = net time averaged velocities.

oscillations become nearly as strong as incident waves over the step near the beach face; subharmonic edge waves are probably responsible for well developed cusps on the locally reflective beach face in the lee of the offshore bar. Longshore currents and offshore rip flows pulse strongly at infragravity frequencies in the rip embayment.

Once the horns of the crescentic bars have welded to the beach, usually in the vicinity of the beach "megacusp" horns to produce alternating transverse bars and rips (Fig. 2d) the most pronounced rhythmic longshore variations in dissipation versus reflectivity, setup, and pressure result. It is under these conditions that the strongest rip circulations occur for any given breaker height. Figure 10 shows the process signature associated with transverse bar and rip topography as exemplified by experiments conducted on the moderately embayed Palm Beach (Fig. 1). The important features are the extremely strong rip currents and rip "feeder" currents. Although these currents remain persistently strong and unidirectional, they alternately strengthen and slacken at infragravity frequencies. On this type of topography, we observe rip current speeds to be typically on the same order as the breaking incident wave orbital velocities. The strong rips, localized by the rhythmic topography related largely to antecedent processes can cause significant scour of rip embayments, even when the adjacent transverse bars are accreting (Short, 1979 a; Short and Wright 1981; Wright 1981).

The ridge-runnel/low-tide terrace state normally prevails only under moderate or low wave energy. Breaking incident waves and their dissipative bores dominate at low tide with low amplitude

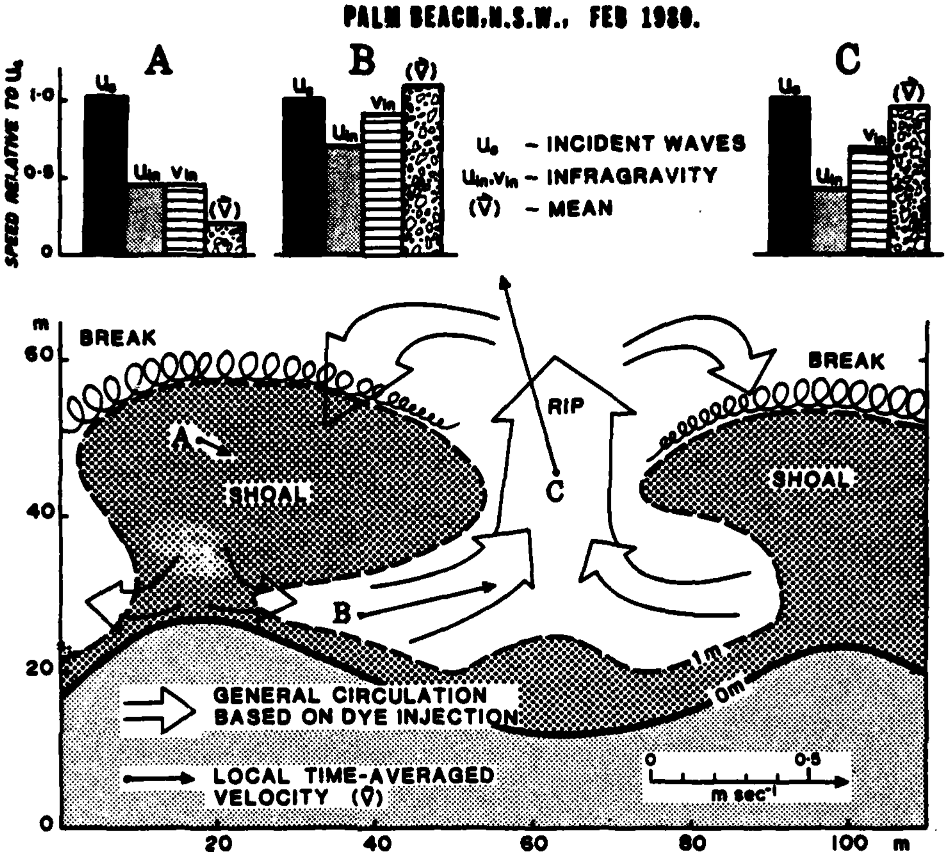

Figure 10: Process signature associated with transverse bar and rip topography (Palm Beach N.S.W., February 1980). Note the strong rips and rip feeder currents.

and relatively high frequency infragravity oscillations making comparatively minor secondary contributions (Wright 1982). Rips are generally weak and irregularly spaced or absent entirely. At high tide, the process signature is similar to that of reflective beaches with incident waves and subharmonic edge waves dominating.

The macrotidal beach

The macrotidal beach (Cable Beach, Broome, W.A.) had a concave upward profile consisting of a subtidal region below extreme low tide level, a low tidal region between the levels of spring and neap low tides, a mid tidal zone between neap low and neap high tide levels, and a high tide zone between neap high tide and spring high tide. The subtidal and low tidal zones were highly dissipative and the high tidal zone was reflective (Wright et al in press). The process signature across the Cable Beach profile is shown in Figure 11 together with the relative frequency that each point on the profile is active. Details of the morphodynamic processes on Cable Beach are discussed by Wright et al (in press).

As shown in Figure 11 the effects of incident waves dominated everywhere across the profile. However, time averaged estimates of wave work over the lunar half cycle (Wright et al in press) showed that most of the work over the subtidal, low-tidal and mid-tidal zones was performed by unbroken shoaling waves rather than by surf zone processes. Surf-zone processes only dominated the reflective high tidal zone which is active for less than 25 per cent of the time (Fig. 11). Standing wave energy, particularly at higher infragravity frequencies (40-50 secs) played important secondary roles on the high tidal zone at spring high tide and over the mid-

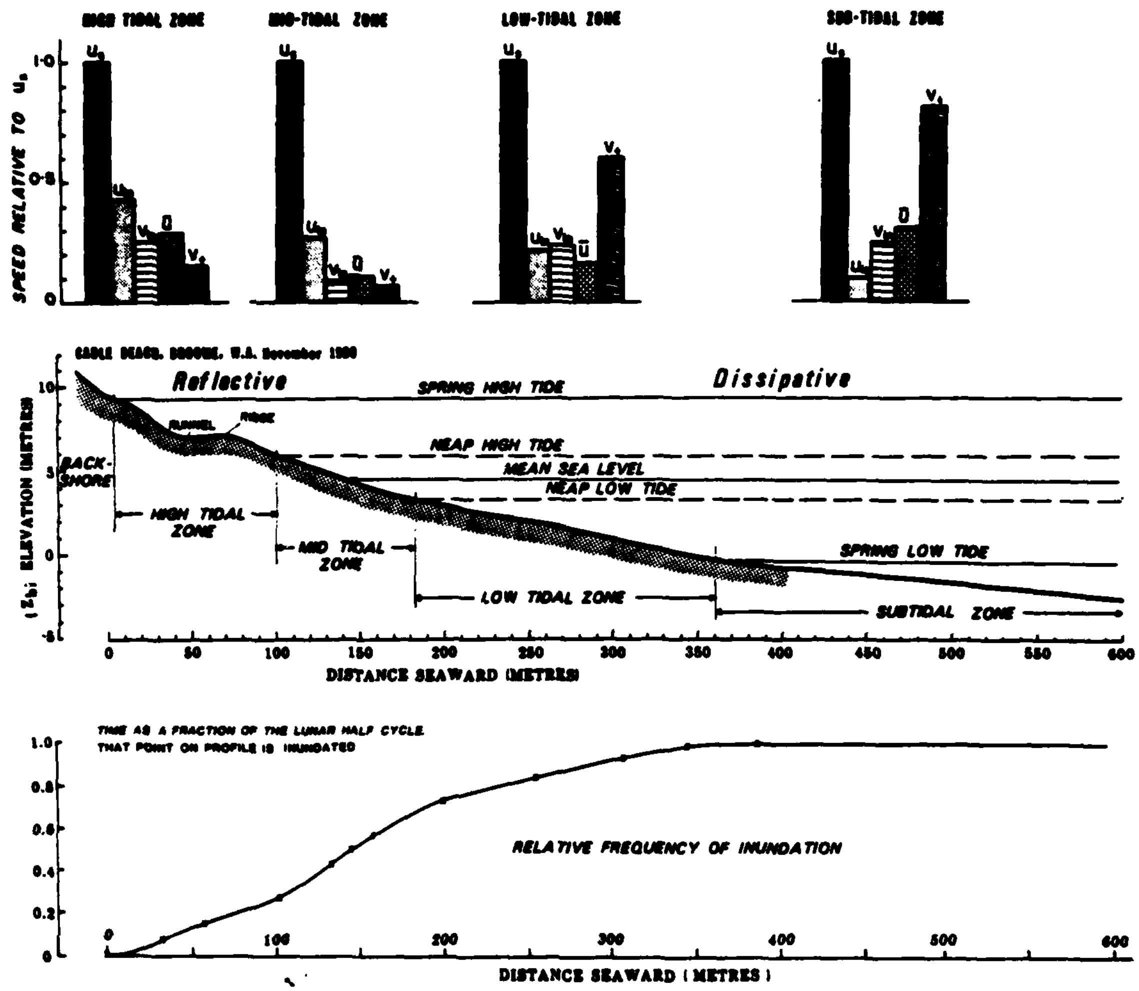

Figure 11: Process signature associated with a macrotidal beach (Cable Beach, Broome, Western Australia, November 1980). The lower curve indicates the fraction of time that corresponding points on the profile are inundated (or active) during a fortnightly neap to spring cycle. The bar graphs have the same meaning as previously except that V_t refers to shore parallel tidal currents.

tidal zone at neap high tide but was of minor importance over most of the profile. A feature which distinguishes the process signature of the macrotidal beach from those of microtidal beaches is the subdominant contribution of strong shore-parallel tidal currents over the subtidal and low-tidal zones. Over the subtidal zone asymmetrical tidal currents, skewed toward the north, attained maximum speeds of 0.5 m sec^{-1} just after high tide. A time series of the currents is shown in Figure 12. These currents were probably responsible for the net longshore transport of sand initially suspended by waves (Wright et al in press; Wright in press). No significant rip cells or wave-induced longshore currents were observed on Cable Beach; however, we have observed them on the high tide portions of other macrotidal beaches.

MODES OF BEACH CUT

In much of the older literature it was considered that whether a beach eroded or accreted depended solely on the height and steepness of the waves. However, it is now clear that the state of the beach immediately prior to and during a high energy or potentially destructive event is equally important. For example it is common for the same set of wave conditions to erode reflective beaches while producing accretion of neighbouring dissipative or intermediate beaches (e.g. Wright et al 1979; Wright 1981). One probable reason for this is the dependence of process signatures on beach state as just discussed in the preceding section. Just as the relative magnitudes of different

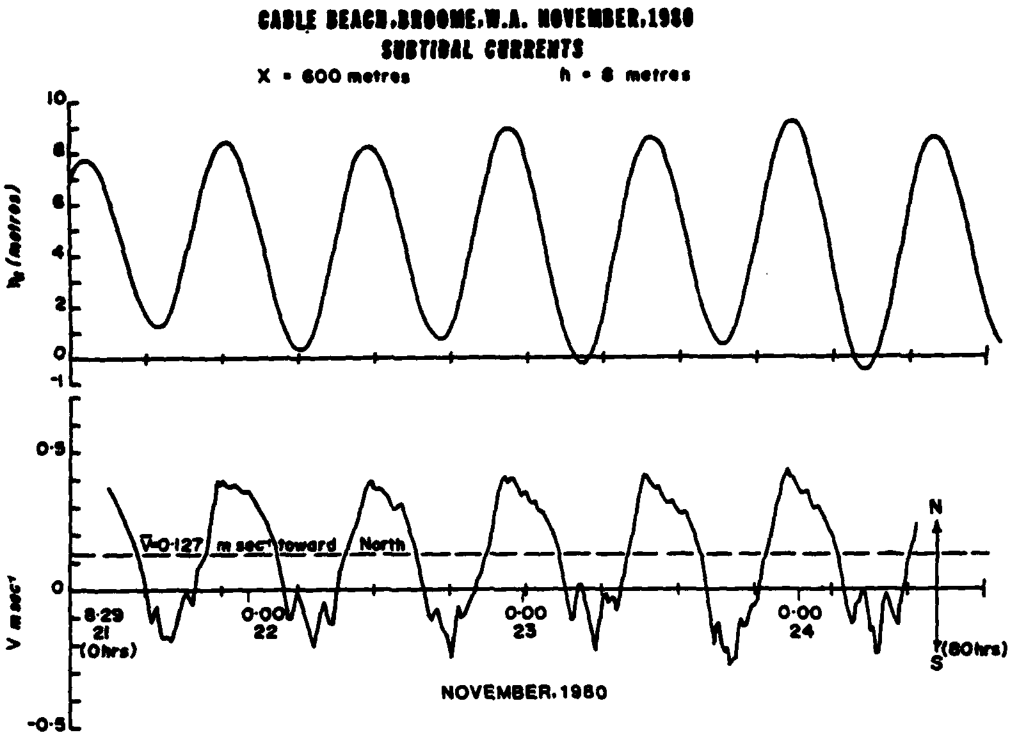

Figure 12: Shore parallel current velocities, V_t as recorded over the subtidal zone fronting Cable Beach from a depth of -8 metres below mean water level. The upper curve shows corresponding tidal elevations, η_t (From Wright et al in press).

modes of sediment disturbing and sediment transporting motion vary with beach state, so also do modes of beach cut. In a recent study, Wright (1981) discriminated between three quasi-discrete but occasionally overlapping modes of state-dependent beach cut. The temporal sequence of beach erosion from a reflective state, through the intermediate to the dissipative state was found to progress through five states (Short 1979 a) each possessing elements of the three erosion modes.

Although the fully reflective beach states represent the accreted extreme of a "beach building" sequence, these states are also the most susceptible to being cut during rising wave energy owing in part to the lack of a subaqueous store of sand (all of the active sand is stored subaerially) and in part to the fact that reflective conditions are conducive to the growth of resonant subharmonic edge waves. Growth of subharmonic edge waves on reflective beaches to amplitudes greater than those of the incident waves under rising long period swell on steep beaches causes accentuated runup. This can cause either beach face scarping or over-topping and initial cutting of the berm (Short, 1979 a). Large, widely spaced erosional cusps are often formed in the early stages of erosion (Wright 1981). Because subharmonic edge waves are easily excited by long period, low steepness swell (Guza and Davis, 1974) this mode of erosion requires the least energy to induce.

Subharmonic resonance is suppressed in turbulent, highly dissipative surf zones. As shown earlier, long period surf beat dominates runup and inner surf zone flows on highly dissipative beaches. However, appreciable wave energy is required to cause surf beat to attain destructive amplitudes so that beaches which are fully dissipative to begin with are the least sensitive to erosion. Nevertheless growth of setup and infragravity oscillations under high energy conditions can allow the bores of partially dissipated waves to penetrate to the backshore or foredune base where scarping occurs. This mechansim can cause dune and backshore recession without necessarily producing a net offshore loss of beach material (Short and Hesp, in press).

Both of the mechanisms of beach cutting just described can operate on intermediate states. In addition, the intermediate states are subject to a third mode of cutting: scour in the embayments of topographically-arrested rips. This mode is most acute in the presence of transverse bar and rip topographies (Short, 1979 a) particularly where the transverse bars remain fixed in position for prolonged periods. Rips can become quite large and highly persistent causing localized chronic erosion problems in regions downdrift from the ebb tidal deltas of tidal inlets or other quasi-permanent or manmade shoreline protrusions (Wright 1981; Wright et al 1980). Because the intermediate states experience all three cutting modes, these states tend to have the highest erosion sensitivity.

On some of the beaches we have studied, notably along the longer straighter ones (e.g. Gippsland) littoral drift plays varying roles in causing net input or output of sand to local beach segments. However, this process is generally not very important on beaches like Goolwa Beach which faces directly into the dominant swell or most of the New South Wales beaches which occupy embayed compartments bounded by protruding headlands. On most of these beaches the most significant removal of sand, when it occurs, is associated with transport processes acting normal rather than parallel to the shore. During high energy events, these processes may move sand offshore to depths of 10 to 20 metres from which it requires 2 years or more to return.

Chronic, long-term recession of the macrotidal Cable Beach is related in large part to northerly longshore transport of sediment out of the region. However, this longshore transport is not attributable to oblique wave approach but rather to asymmetrical shore-parallel tidal currents. The longshore transport process in this case probably simply involves suspension of sediment by shore-normal waves and longshore advection of the sediment by tidal currents (Wright et al in press; Wright in press).

SEDIMENT SUSPENSION IN THE SURF ZONE

Although several investigations have maintained that suspended load transport in surf zones is small relative to bed load transport (e.g. Komar, 1978), those investigations have typically regarded sediment suspension within 10 centimetres of the bed to constitute part of the bed load whereas it should be considered part of the suspended load. This is noted in a recent paper by Bailard (1981). We certainly do not ignore the importance of bed load; however, Nielsen (1979) has shown that where waves agitate the sediment, particularly over rippled beds, much of the transport takes place in suspension. Furthermore, using the suspended sediment profiler developed by our group, we have been able to measure suspended sediment concentrations to within 1 centimetre of the bed. An example of a typical set of concentration profles is shown in Figure 13. The analysis procedures which are explained in detail by Nielsen (1979) Nielsen et al (1979) and Nielsen and Green (in press) permit suspended sediment concentration to be modelled, reliably, right to the bed (or ripple crest) level. We now have over 50 sets of experimental data from different field conditions, on which to base our predictions. Some of these results may be found in recent reports (e.g. Wright et al 1982, in press). The full details are presented in a report to be distributed in the near future (Nielsen and Green in press).

Conventionally, profiles of suspended sediment concentration, c, have been expressed in terms of the one dimensional diffusion equation (e.g. Nielsen 1979). However, more recent work suggests that it is more meaningful, physically, to consider the concentration, c, in terms of a vertical length scale, l, in the form

$$c(z) = C_o \exp(-z/l) \qquad (2)$$

where c(z) is concentration at z elevation and C_o is the concentration at ripple crest level (z = o). In order to predict the concentration profile, c(z) as a function local wave and sediment condition it is thus necessary to predict C_o and l. Nielsen (1979) and Nielsen and Green (in press) have shown that C_o is a function of the skin friction Shield's parameter Θ' (see Nielsen 1979 or alternatively Wright et al 1982 b for the equation for Θ'). Our field data show that C_o is well predicted from

$$C_o = 0.00018\ \Theta'^3 \qquad (3)$$

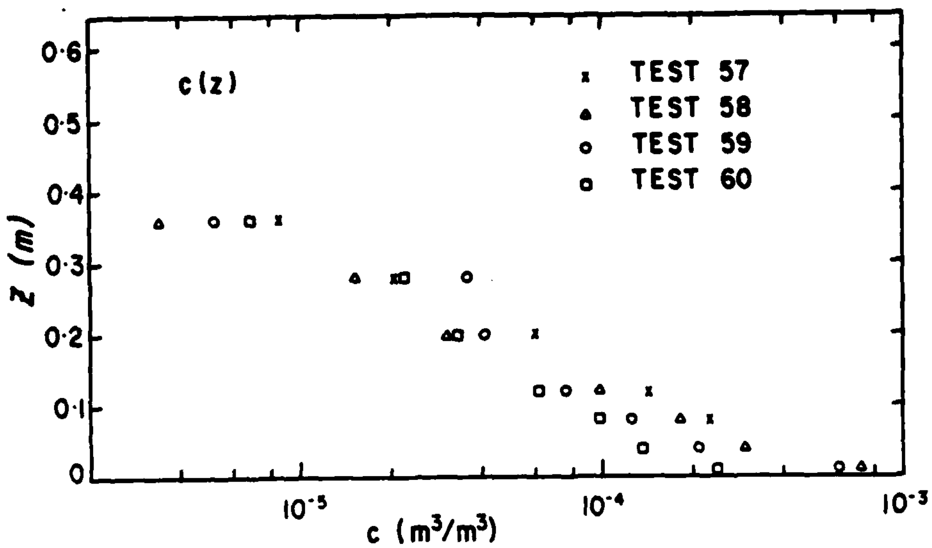

Figure 13: Suspended sediment concentration profiles, (from Eastern Beach, May 1981).

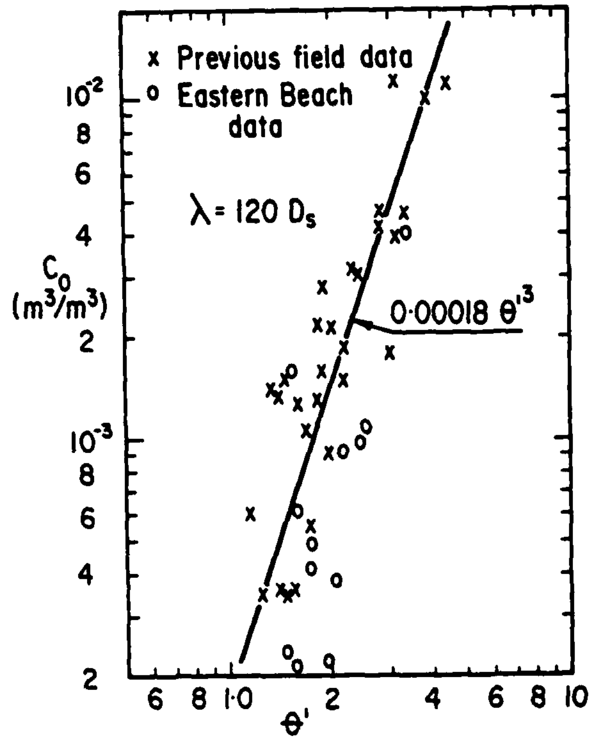

Figure 14: C_o as a function of θ'

a comparison of the curve of equation (3) with the field data is shown in Figure 14. The length scale, l, is a function of ripple heights, η_r, the bottom orbital velocity maximum, U_{max}, and sediment fall velocity, w_s, and gives the best fit to

$$\frac{l}{\eta_r} = 1.43 - 1.25 \exp\left[-.0011\left(\frac{U_{max}}{w_s}\right)^3\right] \tag{4}$$

For plane beds ($\eta_r = 0$), l is roughly equal to boundary layer thickness. Where ripples exist, we still need to know ripple heights, η_r, but Nielsen (1981) showed that η_r can be predicted from the mobility number

$$\Psi = \frac{\rho\, U_{max}^2}{(\rho_s - \rho) g\, D_s} \tag{5}$$

where ρ and ρ_s are water and sediment densities and D_s is grain diameter. The data suggest

$$\frac{\eta_r}{a_s} = \frac{0.23}{1 + 0.022 \exp(\Psi/16)} \tag{6}$$

where a_s is orbital semi excursion.

We can predict suspended sediment concentrations with reasonable confidence under unbroken or broken waves and even when shore parallel wave-driven or tide-driven currents are present (e.g. Wright et al 1982; in press). Unfortunately, quantitative predictions of the rate of net transfer of sediment from one region of the surf zone to another are not so straightforward. To a degree, at least, this involves superimposition of the net flow field on the suspended sediment concentration field. This is a reasonable approach for the alongshore transport where net flow acts perpendicular to wave oscillations. However, when wave oscillations and the net flow are parallel, phase dependency between velocity maxima and concentration maxima introduce complications. In such cases, sediment may move opposite to the direction of net flow.

Despite the difficulties which remain to be overcome before a comprehensive net transport predictive model can be had, the predictive capabilities we presently possess have some very important applications. First, the rate at which surf zone morphology can change must be constrained by the amount of sediment entrained and in suspension. We can therefore assume that the potential mobility of the surf zone is proportional to the total suspended load, integrated over depth and across the surf zone. This can be predicted. A second, and less obvious "spin off" of understanding the relationship between suspended sediment concentration profiles and the length scale, l, is that we have, through our concentration profile data, empirical data concerning l. By being able to predict l, we can also predict the wave-induced, near bottom eddy viscosity. We have shown recently (Wright et al 1982 b) how this relates to the analysis of longshore current profiles like that shown in Figure 8.

MODAL BEACH STATE, TEMPORAL VARIABILITY AND ENVIRONMENTAL CONDITIONS

The morphology of a beach at any particular time is a function of its sediment characteristics, immediate and antecedent wave, tide and wind conditions, and the antecedent beach state. However, over the long term a given beach will tend to exhibit a modal or most frequently recurrent state which depends on environment. The forcing wave climate can, in turn, be described in terms of the modal or most frequently occurring wave condition around which a spread of higher or lower waves may prevail. The beach in response to the wave climate consists of a modal beach type determined by the modal wave conditions, and a range of beach morphologies dependent on the range of the wave conditions. Associated with the temporal variations of beach state around the modal state, is corresponding variation in shoreline position and in profile shape. The range of this variability defines the mobility of a beach. Because the same environmental factors which determine the modal state of a beach also determine its variability, there is a close association between modal beach state and beach mobility. We must now address some fundamental questions concerning prediction of beach and surf zone conditions: What environmental factors determine the modal beach state and probable temporal range of beach states? What roles do inner shelf nearshore processes play in controlling modal beach state and beach state variability? What relationship, if any, is there between modal state and profile mobility?

Modal state and temporal variability of states

From the repeated observations and surveys of specific beaches (e.g. Narabeen, Short 1979 a & b; 1981) it was shown previously that beach state varied largely with wave height when sediment size remained the same. For example intermediate states are favoured by breaker heights of 1-2.5 metres when the beaches are composed of medium sand (Short, 1981). Persistently high waves and an abundance of fine sand result in maintaining the fully dissipative state. Reflective beaches occur under low swell conditions or in sheltered compartments and are often associated with coarse material. It has long been known that beach profiles are controlled by breaker height and period and grain size and we do not propose to reinvent the wheel. However we are concerned, for the moment, with beach state which is not quite the same thing as the profile although the two are certainly related. The point is that beach state is clearly a function of breaker height and period and sediment size; we wish to know more exactly what the relationship is.

In order to place our empirical knowledge in a more universal frame, we must employ some dimensionless parameter, Ω, which incorporates both wave characteristics and sediment characteristics. It makes intuitive sense to follow Dean (1973) and Dalrymple and Thompson (1977) and use a parameter of the form

$$\Omega = H_b/w_s T \tag{7}$$

in which H_b is breaker height, w_s is sediment fall velocity, and T is wave period. There are, of course, other alternatives such as the mobility number Ψ (eq. 5) but we chose Ω as given by (7) because it includes T which our experience indicates to be important. Modal beach state should express the modal value of Ω, whereas the temporal variability of beach state should express the temporal variability of Ω.

Initially, it is worthwhile to identify the threshold values of Ω which separate the reflective and dissipative extremes from the intermediate states. We interrogated all of our available data with two questions: (1) How large can Ω become before a previously reflective beach erodes to become intermediate? (2) How low can Ω drop before fully dissipative conditions are replaced by intermediate states? A value of about 1 defines the reflective/intermediate threshold: Ω must exceed 1 before a reflective beach is transformed into an intermediate beach. Of course, because an adjustment time is required for a beach to change its state, an abrupt drop of Ω to below the threshold will not be immediately accompanied by a change to the reflective state. But if the beach is reflective to begin with, it will not change <u>state</u> so long as $\Omega \leq 1$; if it is not already reflective it will move toward the reflective state. Notably Dalrymple and Thompson (1979) also found $\Omega \sim 1$ to be the threshold between 'normal' accreted (reflective) profiles and 'barred' profiles. At the other end, $\Omega \sim 6$ determines the threshold between intermediate and dissipative conditions. Although fairly large variations in Ω at values greater than 6 can occur (for dissipative states Ω typically ranges from 6 to 30), the morphodynamic state does not change so long as Ω remains above 6. The surf zone width simply expands with increasing Ω and contracts with decreasing Ω. However, once Ω drops below about 6, the intermediate longshore bar-trough state quickly replaces the fully dissipative state. Intermediate states result when $1 < \Omega < 6$. Within this relatively narrow band, the greatest amount of temporal variation occurs.

Figure 15 shows per cent frequency distributions of Ω for different beaches, computed from available long term wave statistics and predicted shallow water modifications by shoaling, refraction

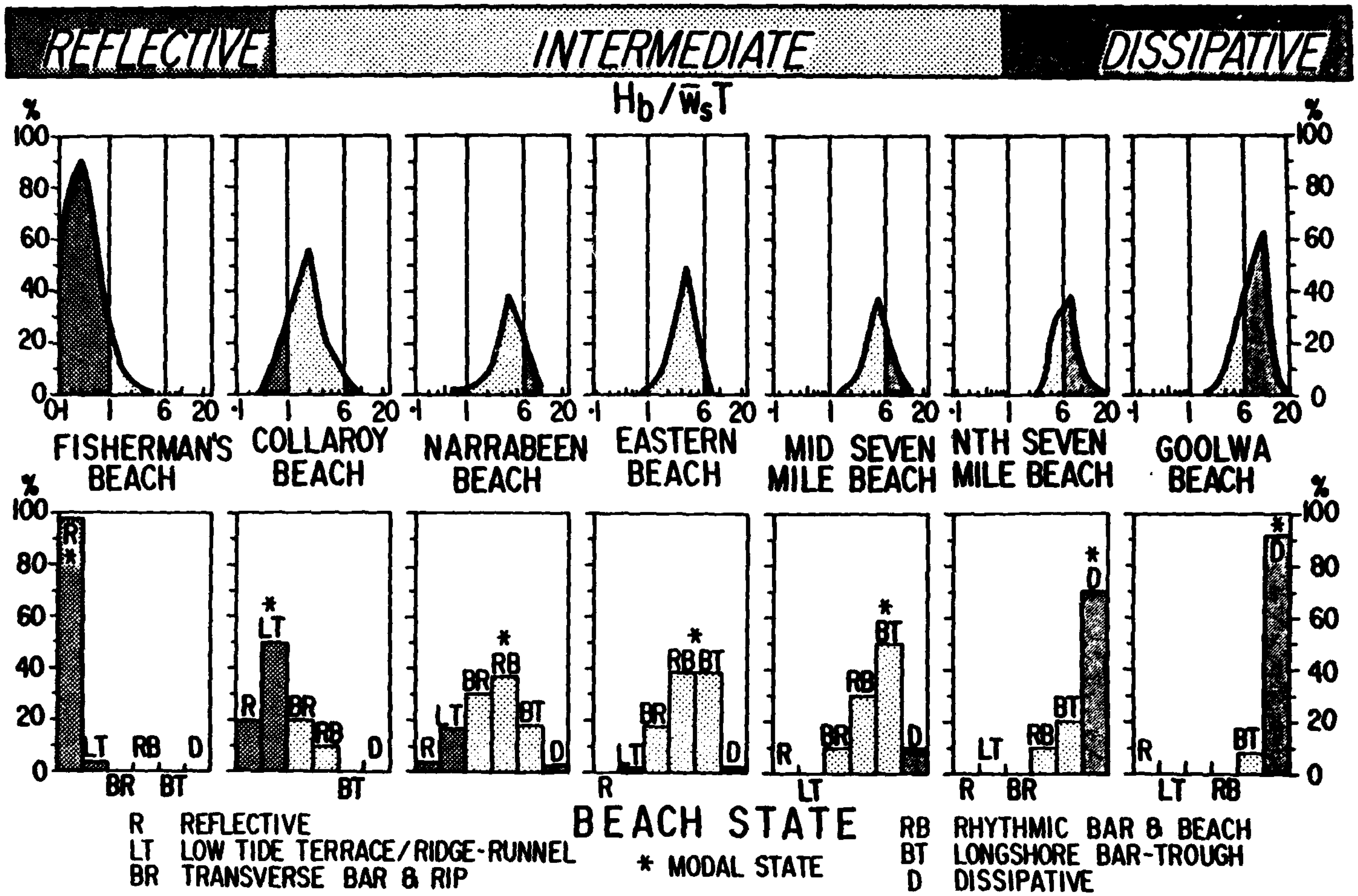

Figure 15: Frequency distribution of $\Omega = H_b/\bar{w}_sT$ and corresponding percentage occurrence of beach states for 7 beaches.

and friction and local sediment characteristics, together with corresponding frequency histograms of beach state. Figure 16 shows plots of modal Ω against modal beach state and the average temporal ranges of Ω and state. Figures 15 and 16 illustrate that when the modal value of Ω is above 6, the modal state of the beach is fully dissipative, when the modal value of Ω is below 1 the modal beach state is reflective, and when the modal of Ω lies between 1 and 6 the modal beach state corresponds to one of the intermediate states. In a general sense, large temporal variations in Ω are accompanied by large variations in state. However, when the variations in Ω, no matter how large, take place solely within the domains of $\Omega > 6$ or $\Omega < 1$, no corresponding variations in state result. The greatest temporal ranges of beach state are associated with large temporal variations in Ω which are centred about modal values intermediate between 1 and 6.

Effects of nearshore wave modification

The modal value and temporal variability of Ω depend on H_b which, in turn, depends on the deepwater wave climate and on nearshore modification of waves by shoaling, refraction and friction. The effects of shoaling and refraction are widely appreciated and require no reiteration here. However, recent developments in understanding the processes of frictional dissipation (e.g. Swart, 1974; Jonsson, 1966; Jonsson and Carlsen 1976; Nielsen in press; Wright et al 1982 b) indicate that this process is probably much more consequential than previously believed. It is now apparent that the roughness and gradient

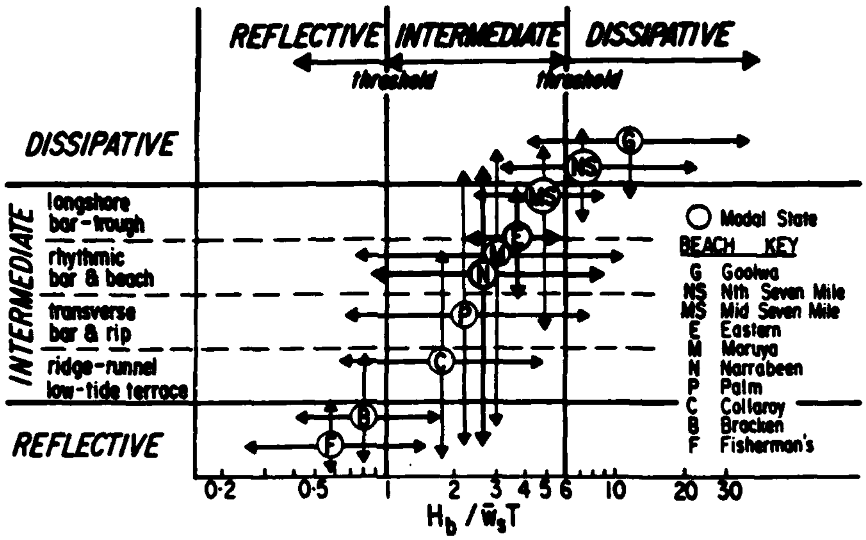

Figure 16: Modal beach state and temporal variability of beach state as functions of the modal values and temporal variability of $H_b/\bar{w}_sT$. Horizontal arrows indicate average temporal range of $H_b/\bar{w}_sT$; vertical arrows indicate average temporal range of beach state.

of the inner continental shelf critically affect not only the modal breaker height but also the frequency distribution of H_b.

The local rate of decrease of wave energy flux, P, is proportional to the cube of the maximum orbital velocity, U_{max} and to the friction factor, f_w in accordance with

$$\frac{dP}{dx} = -\tau u_{max} = -\frac{2}{3\pi}\rho f_w U^3_{max} \tag{8}$$

where τ is shear stress. Since the wave height reduction takes place progressively, the total reduction between deepwater and the break point depends on the integral over the distance between the point at which friction begins and the break point and is thus inversely proportional to the inner shelf/nearshore gradient. In earlier studies (e.g. Bretschnieder and Reid, 1954; Wright, 1976) f_w was considered to be small - on the order of 0.01 - 0.05. However, Swart (1974) showed that f_w depends on the ratio of roughness length, λ to orbital semi-excursion, a_s. Furthermore, Nielsen (in press; see also discussion in Wright, et al 1982 b) has shown that λ is a function of grain size and ripple height and can be large when the bed is rippled and mobile.

It is now clear that when the bed is composed of coarse material and is rippled, f_w, can attain values of 0.30 or greater. As a result, larger reductions in wave height can be expected over rough, low gradient profiles. In addition, since frictional dissipation is non linear and increases with the cube of the wave height, the large waves will experience more attenuation than the small ones. This can have the effect of reducing not only the modal wave height but also temporal variability. Details concerning the estimation of λ, f_w, and total dissipation may be found in Wright et al (1982 b) and in Nielsen (in press).

The roles of nearshore gradient and roughness are illustrated by a comparison of Narrabeen Beach with Eastern Beach. As shown in Figure 16, the modal Ω values and modal state of the two beaches are similar. However, whereas Narrabeen exhibits a wide range of Ω and the full possible range of beach states, the variability of Ω and state on Eastern Beach are confined to narrow intermediate bands. The variability of deepwater wave conditions is broad in both cases; the differences are related to differences in nearshore frictional dissipation. Figure 17 shows the nearshore profiles fronting the two beaches together with the probability distributions of deepwater wave heights H_∞ and breaker height H_b.

The Narrabeen profile is steep and narrow while the Eastern Beach profile possesses a very wide, low gradient plain between the 15 metre and 20 metre depth contours. In addition, the Narrabeen profile is composed of fine to medium sand with only small ripples normally present and hence has a small roughness. Coarse sand and gravel and wave ripples on the order of 10 centimetres high mantle the low gradient plain fronting Eastern Beach, producing a very rough surface (Wright et al 1982 b). Accordingly, the friction factor, f_w, associated with Narrabeen and Eastern Beaches have respective estimated values of 0.09 and 0.25. Much more frictional dissipation takes place seaward of Eastern Beach. The effects are evident from the probability distributions of H_b. In the Narrabeen case, shoaling approximately balances the small amount of dissipation so that the probability distribution of breaker height remains very close to that of the deepwater height. For

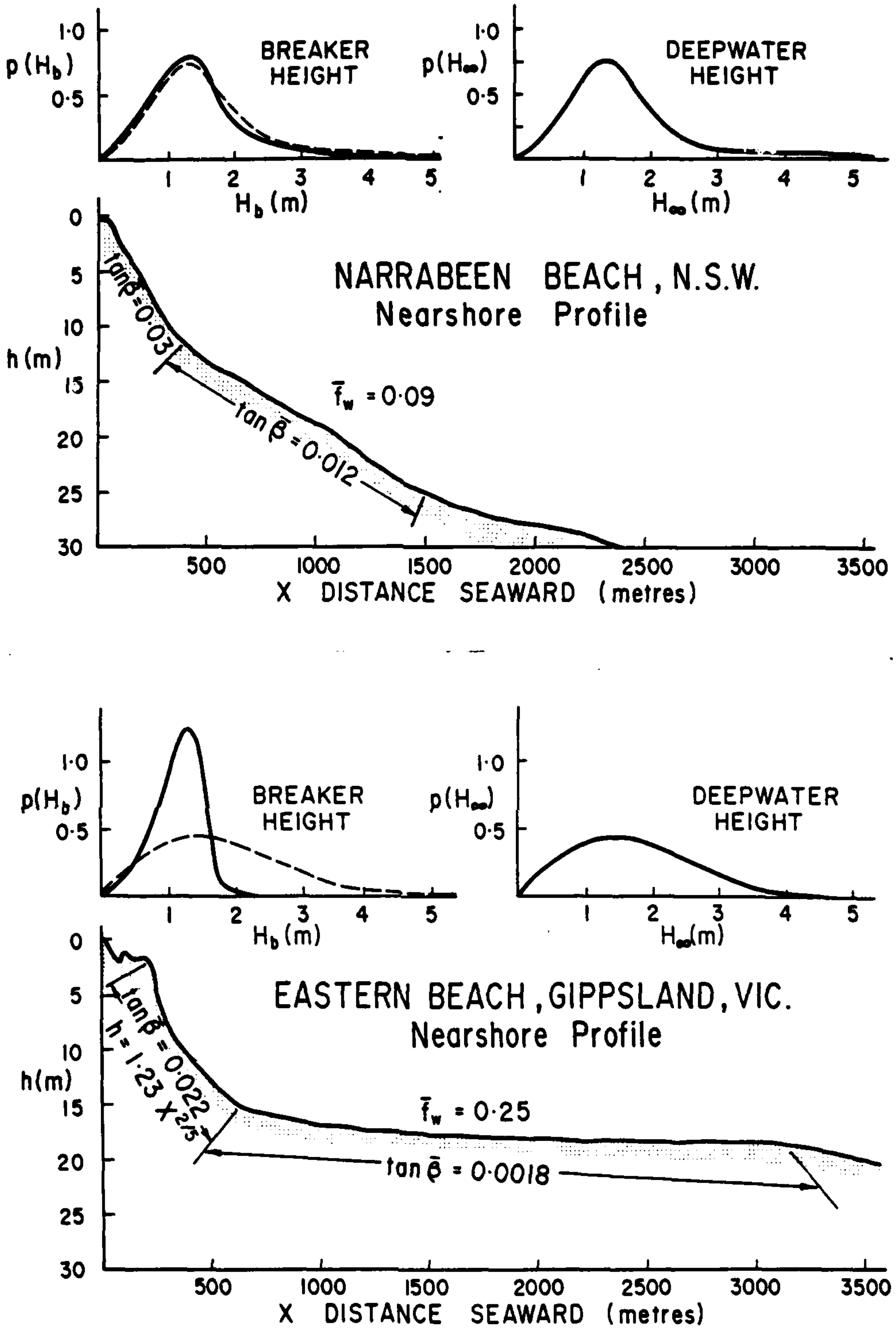

Figure 17: Nearshore profiles fronting Narrabeen and Eastern Beaches together with probability distributions of deepwater height and breaker heights after modification by shoaling, refraction and friction.

Eastern Beach, however, we see not only a significant reduction in modal breaker height, but more importantly an appreciable narrowing of the temporal variation of H_b: although H_∞ may frequently exceed 4 or 5 metres we expect H_b rarely to exceed 2 metres. Hence, Eastern Beach rarely attains the fully dissipative state (Wright et al, 1982 b).

Profile mobility in relation to modal state

We might expect that when the temporal variability of beach state is high the mobility of the associated beach and surf zone profiles will also be high. This is the case. As indicated by Figures 15 and 16 intermediate modal states are typically related to fairly large variabilities of state. In addition, when beach state is intermediate, considerable change in the absolute profile can take place without the state changing. There is thus a relationship, albeit a causally complicated one, between profile mobility and modal state (Wright and Short in press).

Figure 18 shows the profile envelopes of temporal variation, or "sweep zones" of several beaches together with bar graphs indicating the corresponding modal states and state variability. Low temporal variability of the beach and surf zone profile is associated with both modally reflective and modally dissipative beaches. In the reflective case, berm heights and step depth vary with changes in breaker heights, but beach gradient changes little and the beach advances and retreats over a narrow horizontal distance. Increases and decreases in breaker height over modally dissipative beaches cause widening and contraction of the surf zone width and may respectively cause backshore scarping and accretion. However, the horizontal

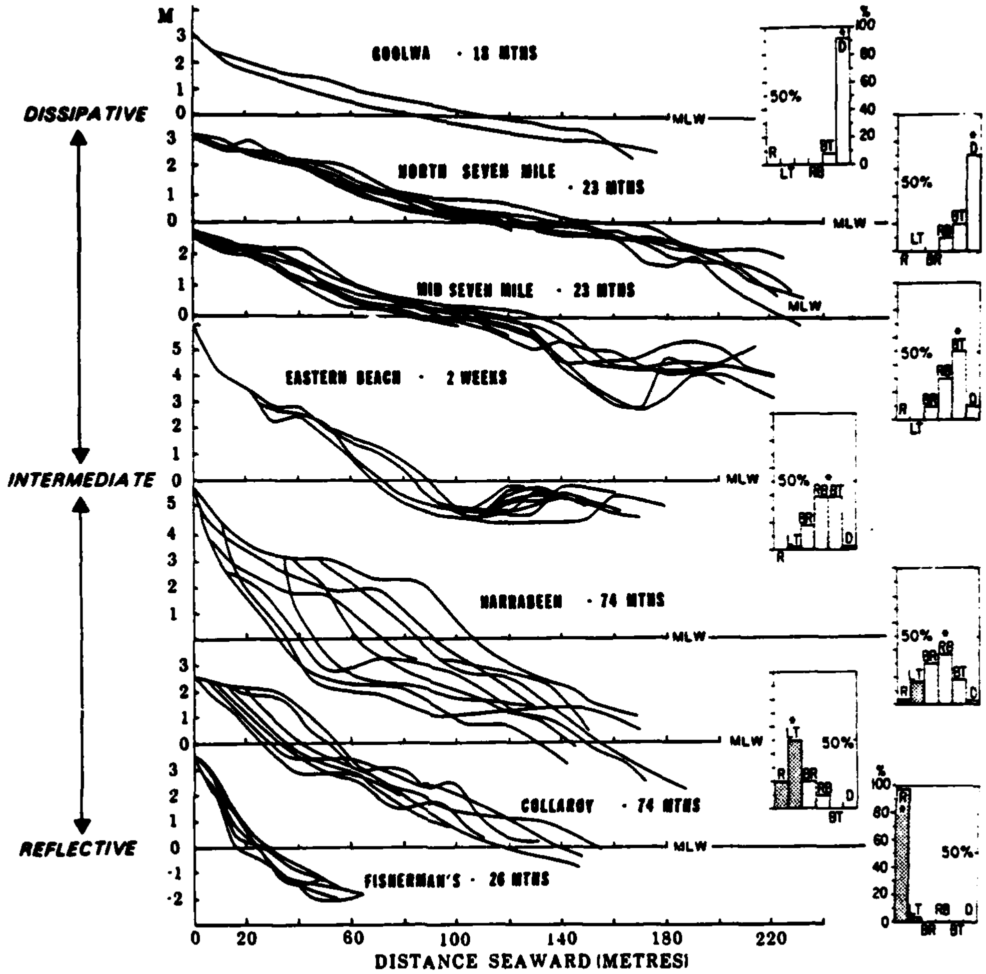

Figure 18: Beach profile mobility in relation to modal beach state and state variability.

range of shoreline position and vertical range of changing sand surface elevations are small. The low temporal variability of the reflective and dissipative extremes is paralleled by low spatial variability alongshore (Short and Hesp, in press).

Intermediate beaches are spatially and temporally the most dynamic beach forms. With their characteristic rip circulation, dynamic bar forms, abundant surfzone and beach sediment and moderate waves, they can undergo rapid changes as wave height fluctuates causing rapid reversals in onshore-offshore and alongshore sediment transport. As one might expect considering the complex process signatures of these states, the mobility of modally intermediate states is higher than that of either of the two extremes (Short and Hesp, in press).

Bar and surfzone features are particularly mobile on both longshore bar-trough and rhythmic bar and beach topographies. However, the straight reflective subaerial beaches of the longshore bar-trough state, partially sheltered by the offshore bar, normally exhibit only low to moderate variability (e.g. Wright et al 1982 b). In contrast the inherent spatial (longshore) variability of the rhythmic bar and beach states combines with the high temporal variability of the bar producing high mobility of both the bar and the beach face. In the case of the low-tide terrace/ridge and runnel state, the close proximity between the "bar" and the beach face permits rapid exchange of sand leading to moderate to high temporal variability.

Frequency-response, equilibrium, and rate of change

Figures 15, 16 and 18 cannot, of course, convey the full story concerning the temporal variability of beach state or profile. One reason for this relates to the frequency-response characteristics of beach and surf zone morphodynamics. Quite simply, the time required for the beach and surf zone to evolve from one equilibrium state to another will be inversely proportional to the mass of sediment needing to be redistributed and proportional to the available energy. If H_b changes too rapidly the full beach response will not result. Futhermore, response to low energy events will be slower than response to high energy events. For any given energy level, the rate of change in state, profile or other morphodynamic parameter should be greatest when the departure from the equilibrium state is largest and should decrease as equilibrium is approached. These concepts are illustrated by Figure 19.

It is relatively axiomatic to state that morphodynamic changes result from gradients in sediment transport. When the divergence of sediment transport is zero everywhere, the time derivative of state, beach slope, or shoreline position etcetera will also be zero and equilibrium will exist. Each of the extreme and intermediate states may exist as the equilibrium state in association with an appropriate set of conditions, Ω. (In this context, however, the correct form of Ω may be something other than $H_b/\bar{w}_sT$). We can thus conceive of an equilibrium curve of the sort shown in Figure 19. When the instantaneous conditions depart appreciably from this curve and when the energy is high the rate of change, ds/dt, should be large.

The maximum range of temporal variability will be inversely proportional to the rate at which Ω changes. That is, if Ω oscillates over short periods of time, the full range of projected equilibrium

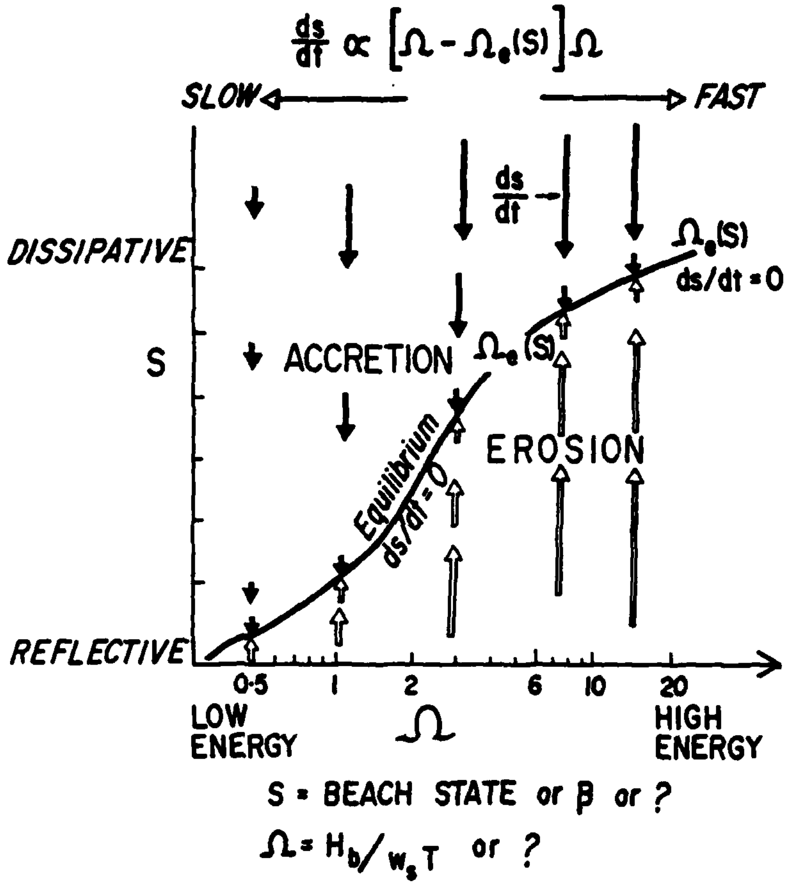

Figure 19: Conceptual diagram illustrating some relationships between morphodynamic equilibrium, relative energy, and relative rates of erosion or accretion.

adjustments will not be attained. On the east coast of Australia, high energy storm events can cause a shift of beach state from reflective or intermediate to dissipative in a matter of days because the energy is high. The return to reflective conditions under low energy can require weeks or months or longer (e.g. Short, 1979a). In environments where the dominant variation in wave height corresponds to an annual cycle of change (e.g. high storm waves in winter, low swell in summer) the full sweep from a dissipative "winter" profile to a reflective "summer" profile may be expected. Such a model does apply to the environments of eastern Australia and probably does not apply to many other parts of the world (Short, 1979a).

Spectral analyses of 11 years of daily mean deepwater wave height (wave rider data) from offshore of Sydney, shows that only 5% of the variance in wave heights is associated with the annual cycle. An equal amount corresponds to a biennial cycle. Most of the variance (55%) takes place in association with cycles less than 1 month in duration. In the case of Eastern Beach in the storm wave environment of Bass Strait, the average interval separating occasions of waves greater than 2 metres is only about 3 days (Wright et al 1982 b). The waves there do not remain small long enough for the reflective state to develop. In addition, large breaker heights are precluded by nearshore frictional dissipation so that the range of intermediate states remains narrow.

What is now required is to quantify more explicitly the equilibrium curve and rates of change, illustrated loosely in Figure 19. When this is done short-term predictability of beach behaviour will be at hand. Analyses of our long-term time series of beach state, beach profiles, and wave conditions are proceeding along those lines.

CONCLUSIONS AND PROGNOSIS

If beach profiles were simple, as is roughly the case for the reflective and dissipative extremes, and if breaking waves were the only source of fluid motion acting to move sediment, which is not the case for any of the natural states, then predicting beach changes would probably be a relatively simple matter. In such an ideal world, we could probably rely on the results of laboratory experiments without much loss of confidence. Unfortunately, the existence of complicated and widely prevalent intermediate states, the prominent roles played by various standing wave and edge wave modes and by various scales of surf zone circulation, the importance of inheritance from antecedent states, and the roles of processes acting seaward of the surf zone make the natural environments less simple.

Nevertheless, repeated observations of nature have shown that the morphodynamic associations are at least quasi-systematic though not yet fully predictable. Predictability is certain to be improved progressively through continued observation, data collection and analyses. Extension of the predictive models to a universal or global scale will require more intensive use of remote sensing data since experiments of the sort we have discussed can never be carried out worldwide.

From our results so far, it becomes increasingly apparent that the onshore-offshore and alongshore exchange of sediments is not confined to the surf zone but extends out onto the inner continental shelf to depths of over 20 metres. In addition, processes operating over the inner continental shelf partially predetermine the nature, intensity, and variability of the processes which operate within the surf zone. An example is presented in this report; others are discussed by Wright et al (1982 b). In turn, the complex processes of the surf zone are fundamental in effecting the transfer of sediments between the shelf and the subaerial beach. The problem of beach and nearshore morphodynamics is thus one which involves the entire Coastal Boundary Layer (Fig. 20). The Coastal Boundary Layer is defined in this context as the region in which oceanic processes are measurably modified by the presence of the coast. The seaward limit is approximately the 50 metre depth contour and the landward limit is the beach. In the future we must be concerned with morphodynamic aspects of the Coastal Boundary Layer including the region seaward of the surf zone, the surf zone, and the beach.

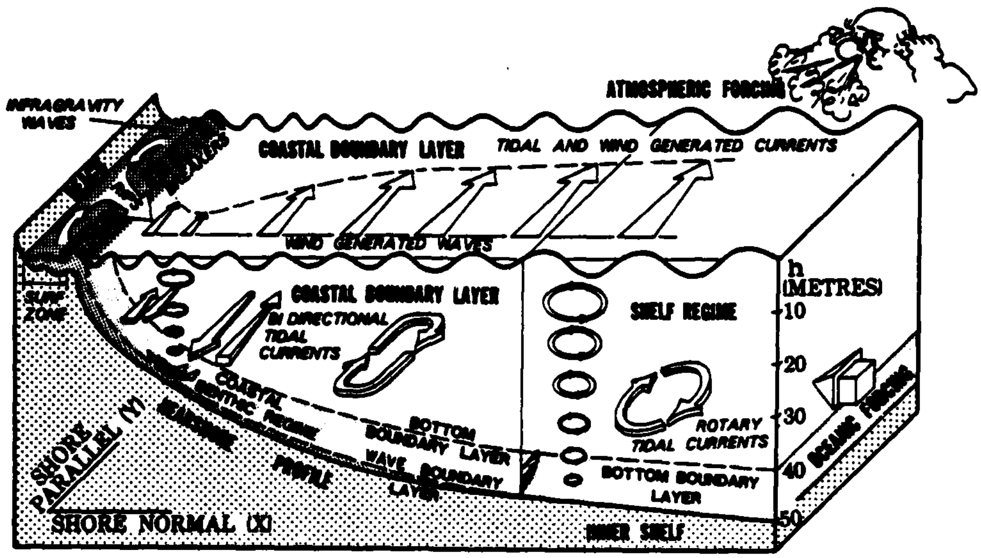

Figure 20: Some components and processes of the Coastal Boundary Layer. We must now address beach and surf zone morphodynamics in the context of this larger system.

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A short, simplified synthesis of some results obtained over the period 1979-1982 from a study of beach and surfzone dynamics is presented. The report deals with the different natural beach states, the process signatures associated with these states, state dependent modes of beach erosion, the status of predicting wave- and surf-induced sediment suspension, environmental controls on modal beach state, and the temporal variability of beach state and beach profiles.

Hydrodynamic processes and the relative contributions of different

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) mechanisms to sediment transport and morphologic change differ dramatically as functions of beach state, that is depending on whether the surf zone and beach are reflective, dissipative or in one of the several intermediate states. Depending on beach state, near bottom currents show variations in the relative dominance of motions due to: incident waves, subharmonic oscillations, infragravity oscillations, and mean longshore and rip currents. On reflective beaches, incident waves and subharmonic edge waves are dominant. In highly dissipative surf zones, shoreward decay of incident waves is accompanied by shoreward growth of infragravity energy; in the inner surf zone, currents associated with infragravity standing waves dominate. On intermediate states with pronounced bar-trough (straight or crescentic) topographies, incident wave orbital velocities are generally dominant but significant roles are also played by subharmonic and infragravity standing waves, longshore currents, and rips. The strongest rips and associated feeder currents occur in association with intermediate transverse bar and rip topographies.

Field observation and modelling of sediment entrainment and suspended load concentrations can be modelled accurately, to bed level, in terms of the skin friction Shield's parameter and a length scale which is also predictable. Important ripple dimensions can also be predicted on the bases of wave height, wave period, depth and grain size. Total or local suspended loads can be predicted as a function of wave characteristics, depth, bed roughness, and sediment fall velocity. In a practical sense, the predicted total quantity of sediment entrained above the bed provides a meaningful index of the potential mobility of the surf zone.

Long-term consecutive surveys of different beaches with contrasting local environmental conditons provide the data sets for empirical-statistical assessment of beach mobility, direction of change and response to environmental conditions. Conditions of persistently high wave energy combined with abundant and/or fine grained sediment results in maintaining highly dissipative states which exhibit very low mobility. Relatively low mobility is also associated with persistently low-steepness waves acting on coarse-grained beach sediments. In such cases the modal beach state is reflective. The greatest degree of mobility is associated with intermediate but highly changeable wave conditions, medium grained sediment and a modest or meagre sediment supply. Under such conditions the beach and surf zone tends to alternate among the intermediate states and to exhibit well developed bar trough and rhythmic topographies. A good association is found between beach state and the environmental parameter $\Omega = H_b/\bar{w}_s T$ where H_b is breaker height, $\bar{w}_s$ is mean sediment fall velocity and T is wave period. Temporal variability of beach state reflects, in part, the temporal variability and rate of change of Ω, which, in turn depends on deepwater wave climate and nearshore wave modifications.

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